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BULLETIN NO. 41

TESTS OF TIMBER BEAMS

BY

ARTHUR N. TALBOT

UNIVERSITY OF ILLINOIS
ENGINEERING EXPERIMENT STATION

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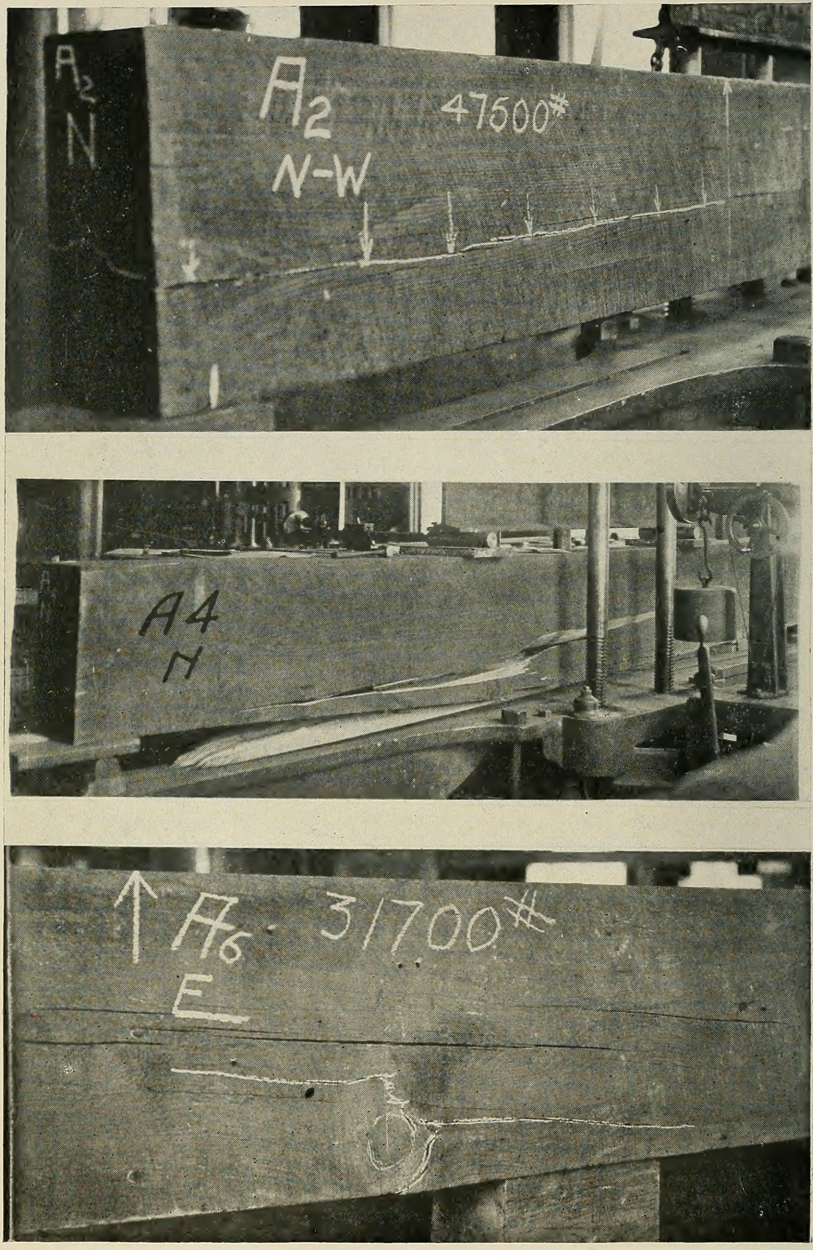
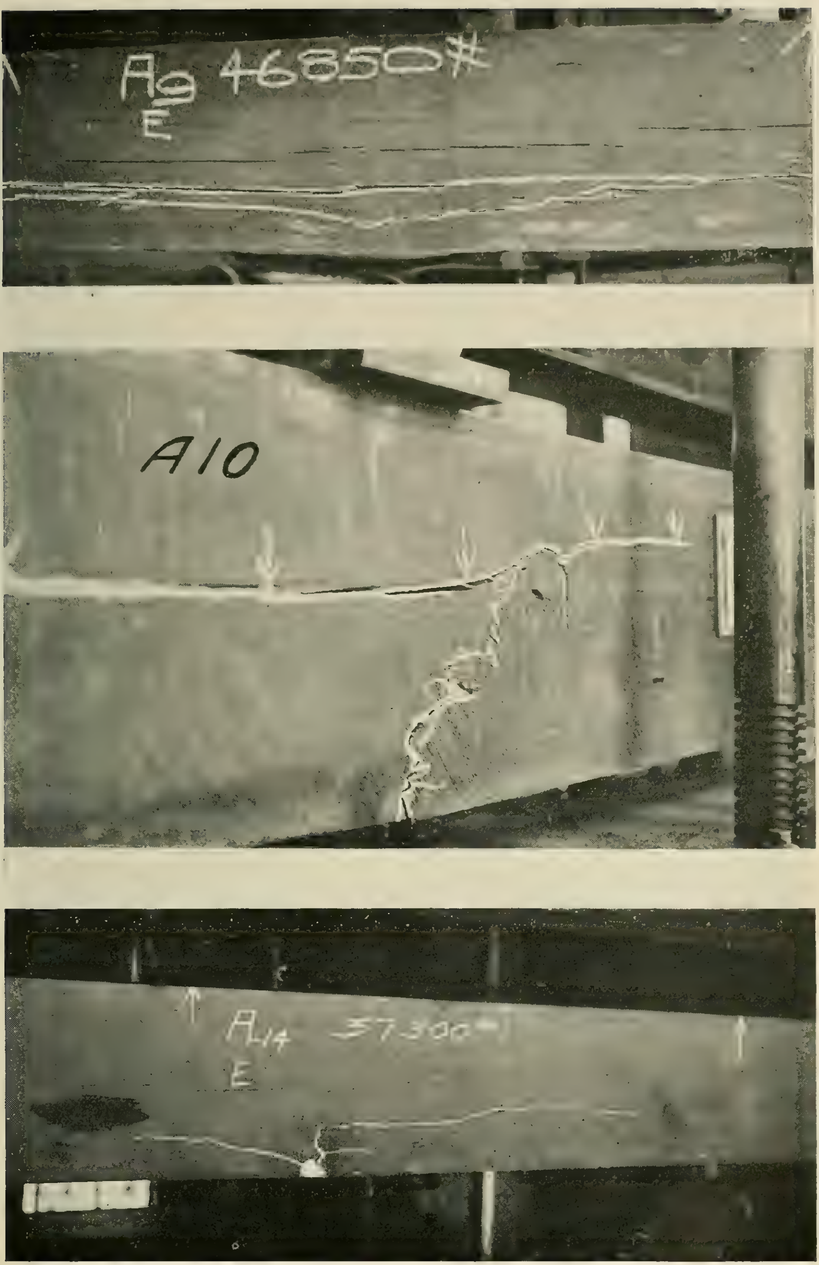


PLATE 1. VIEWS OF BEAMS AFTER FAILURE.



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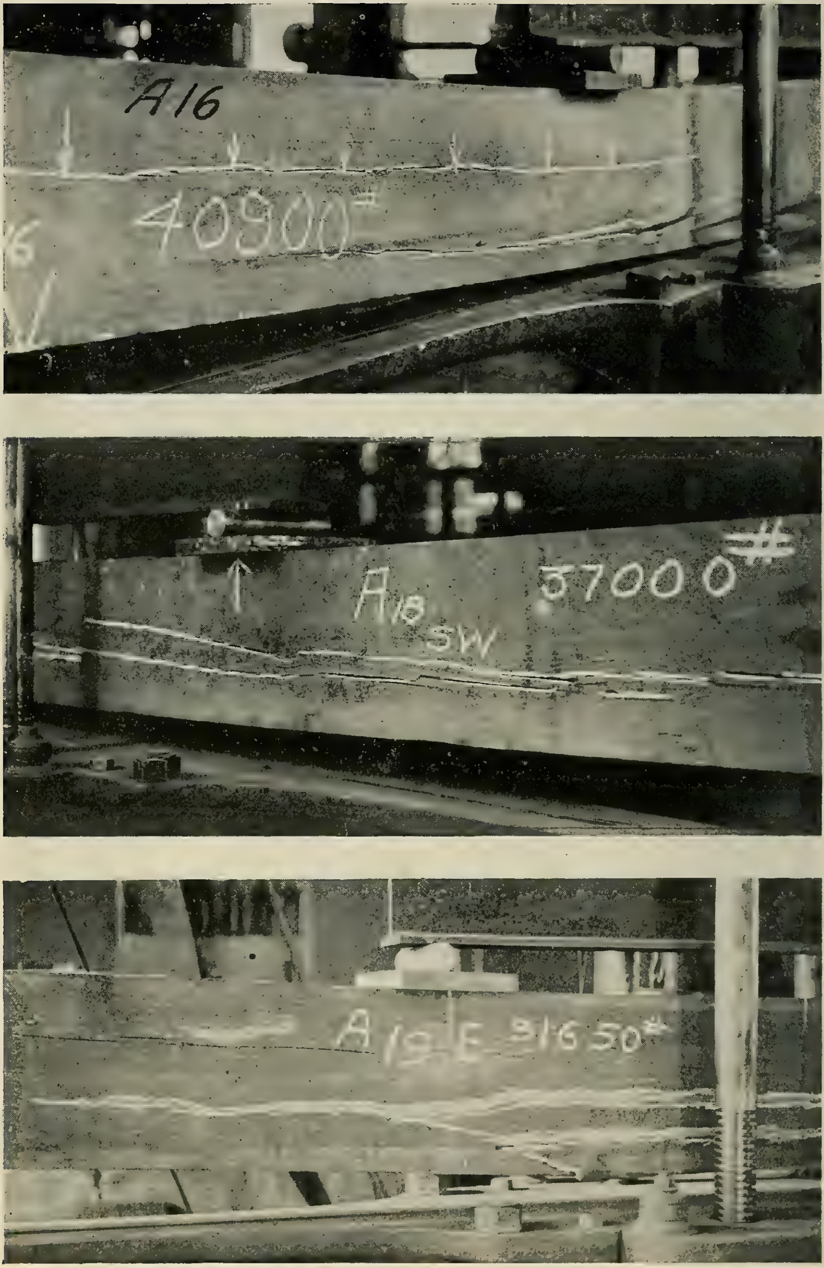

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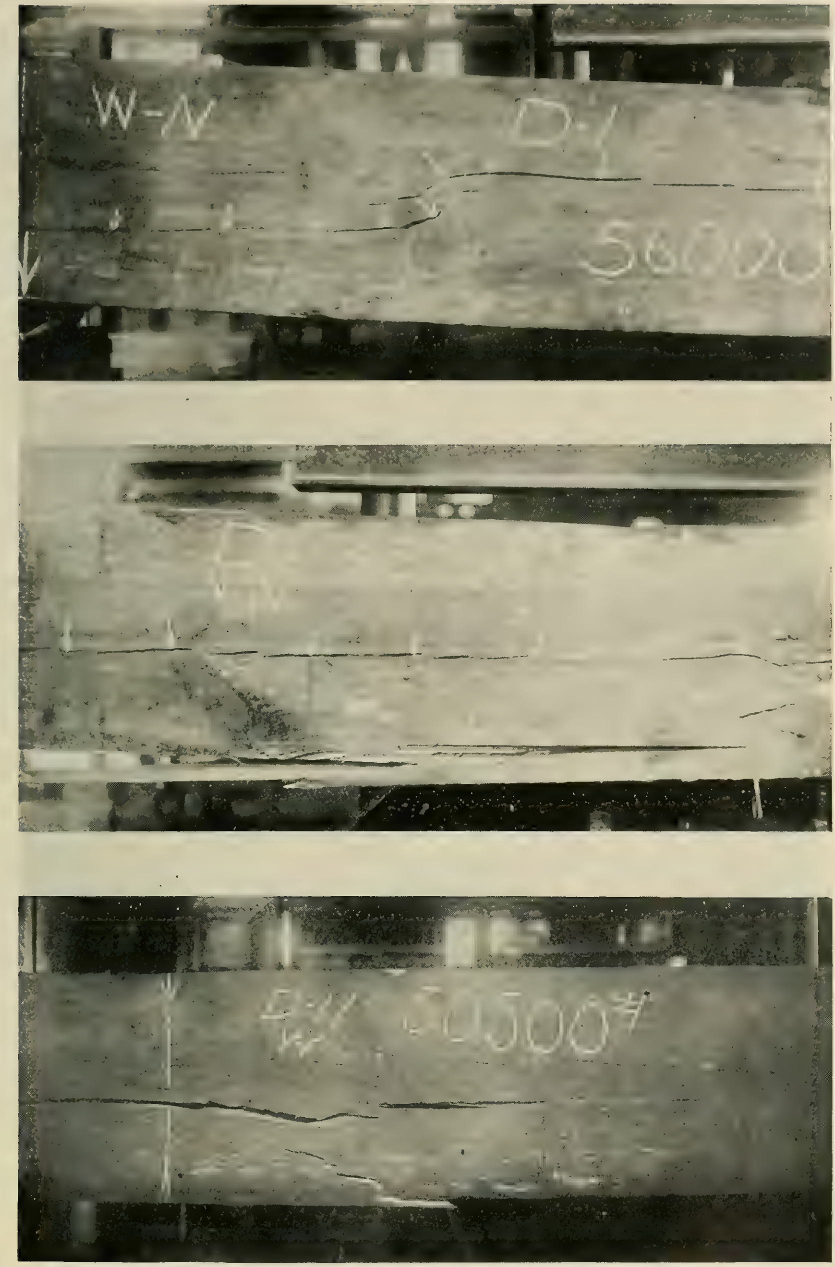

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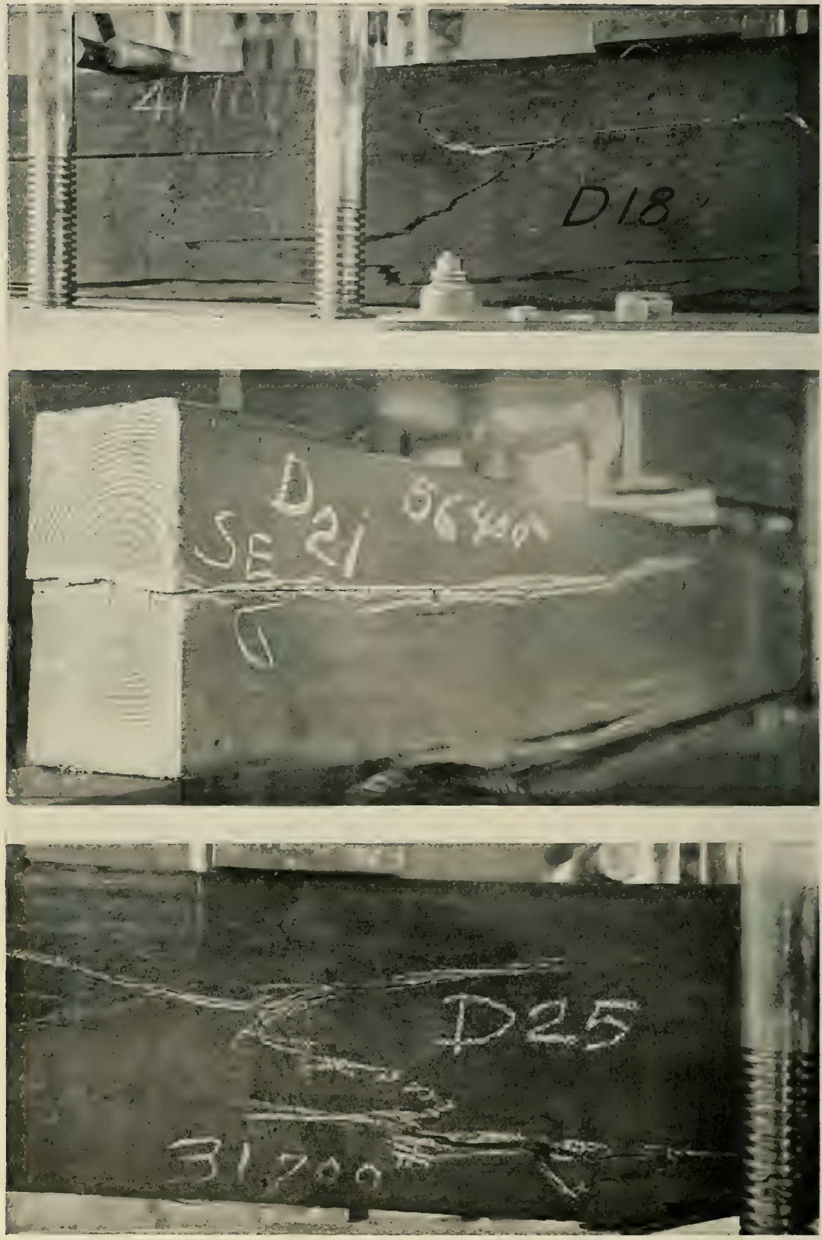

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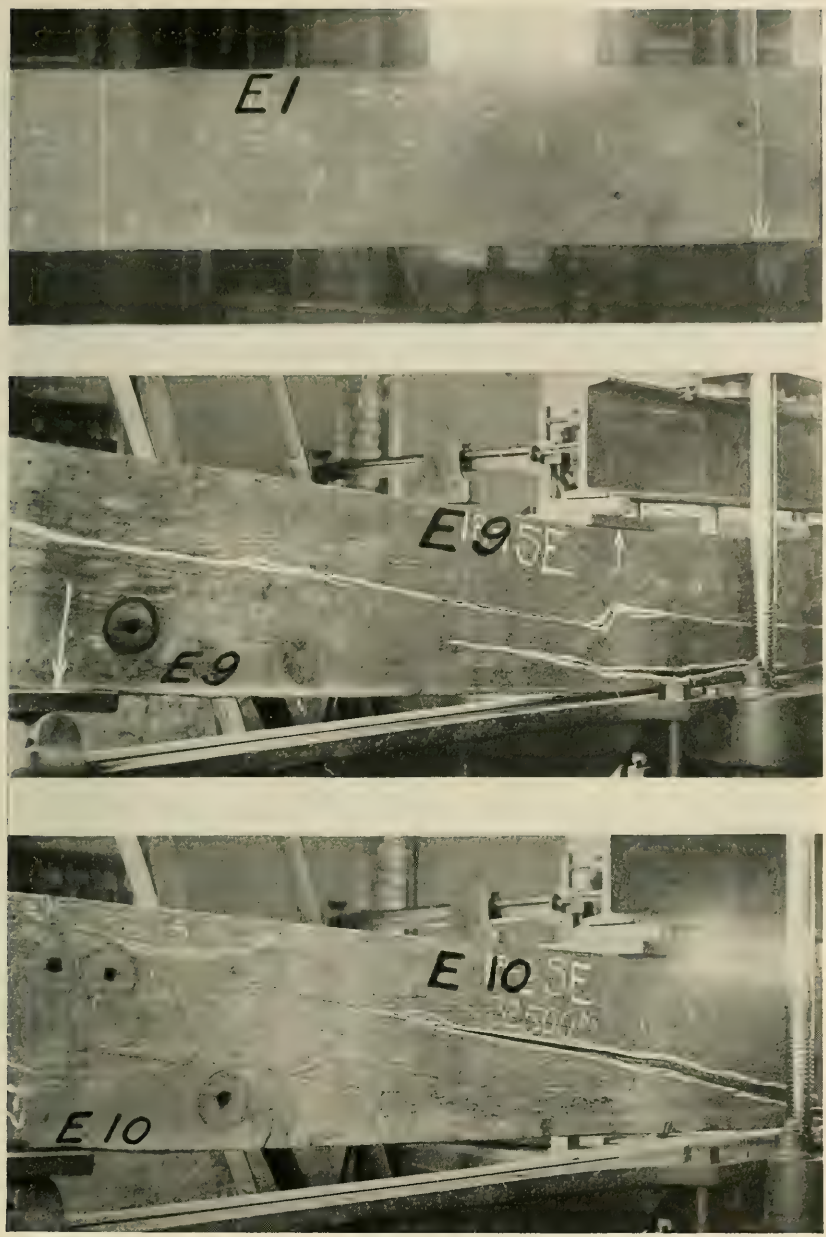

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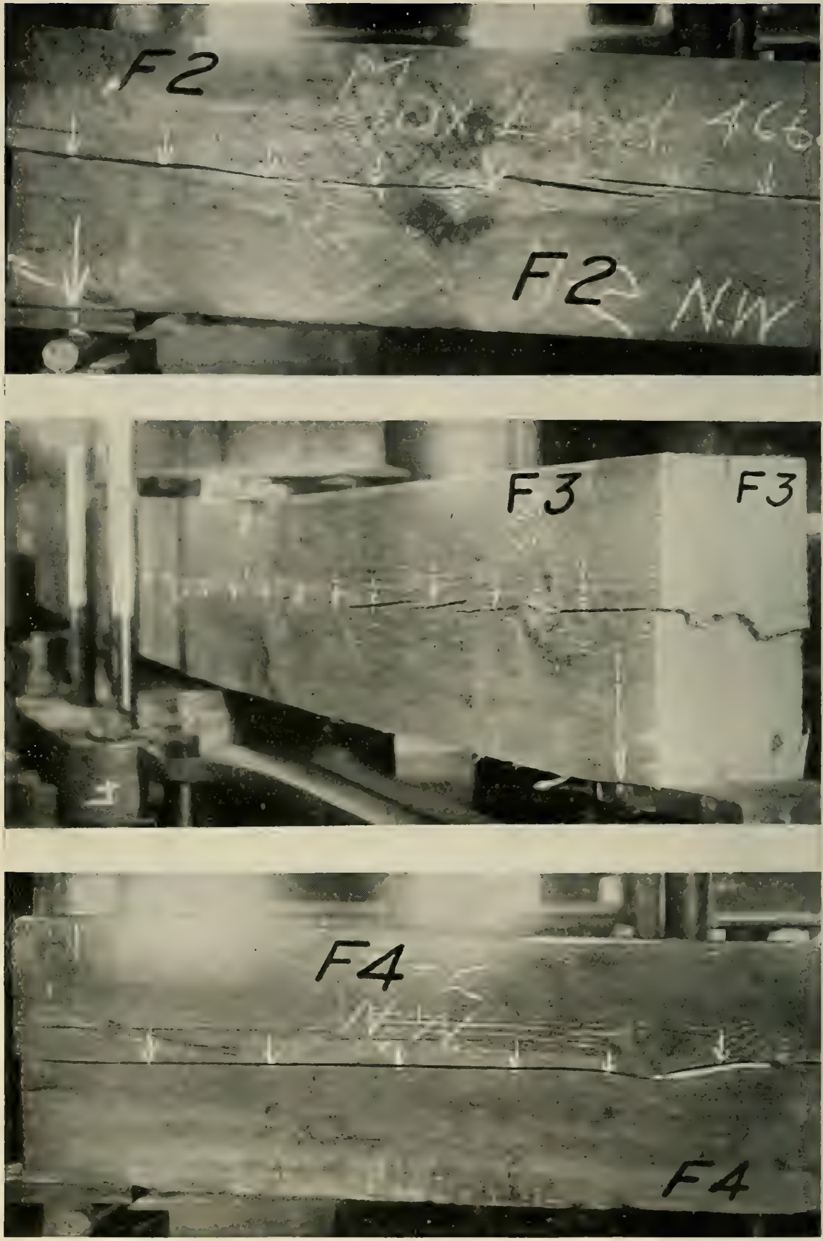


Plate 7. Views of Beams after Failure.

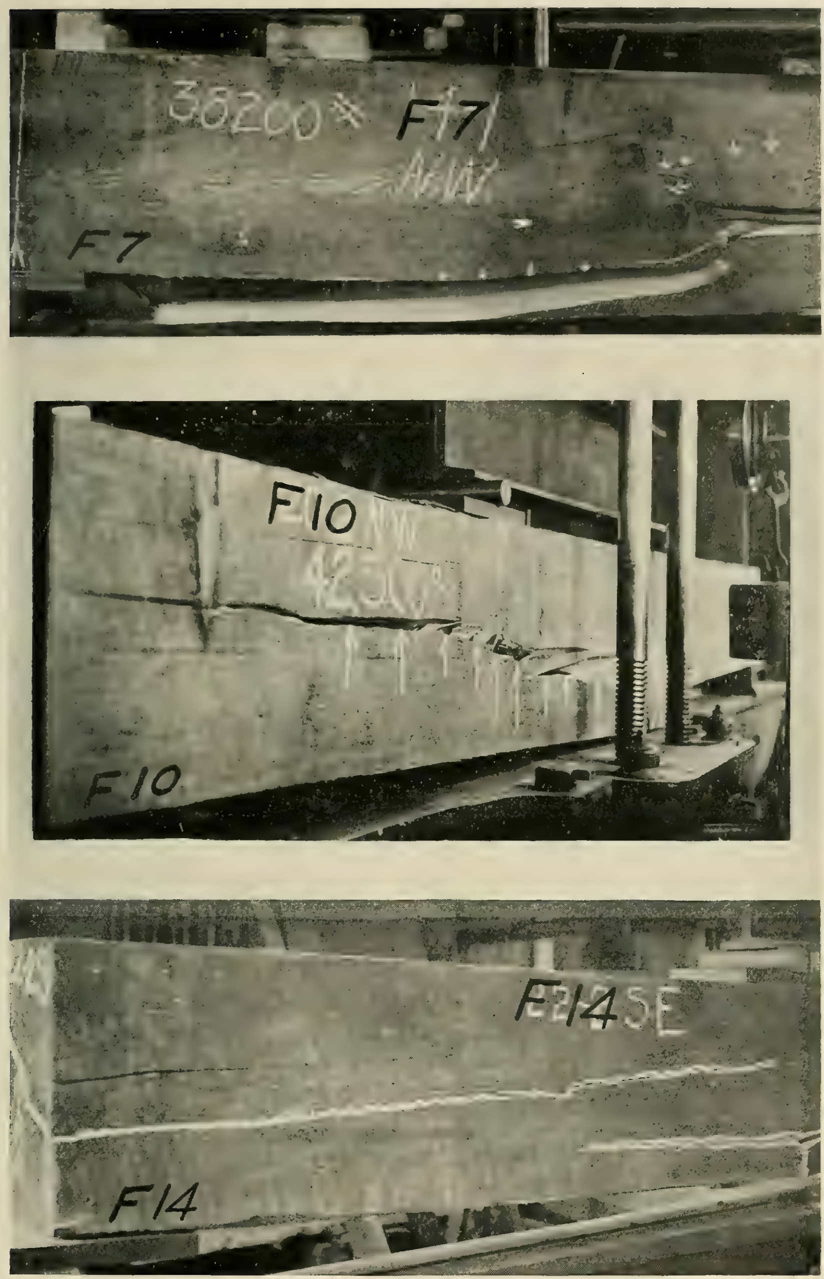


Plate 8. Views of Beams after Failure.

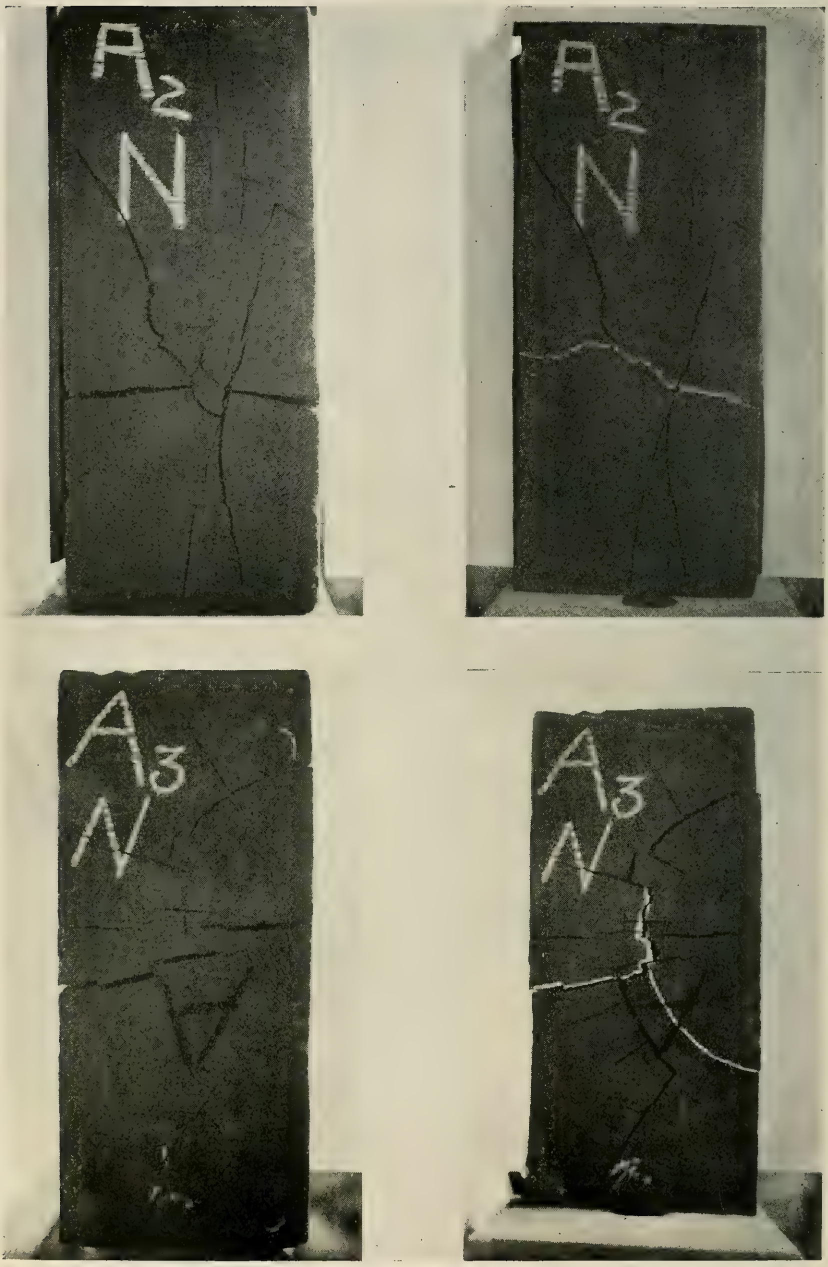


PLATE 9. VIEWS OF ENDS OF BEAMS BEFORE AND AFTER FAILURE.

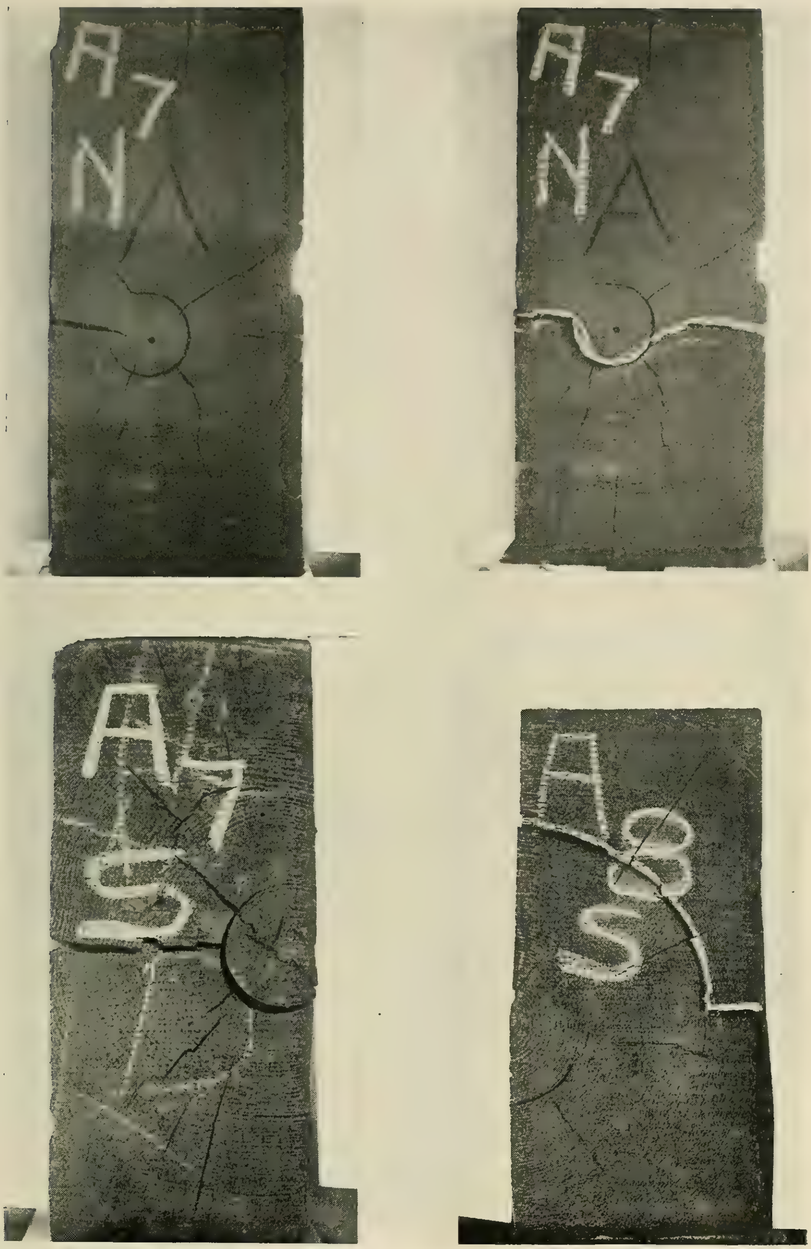
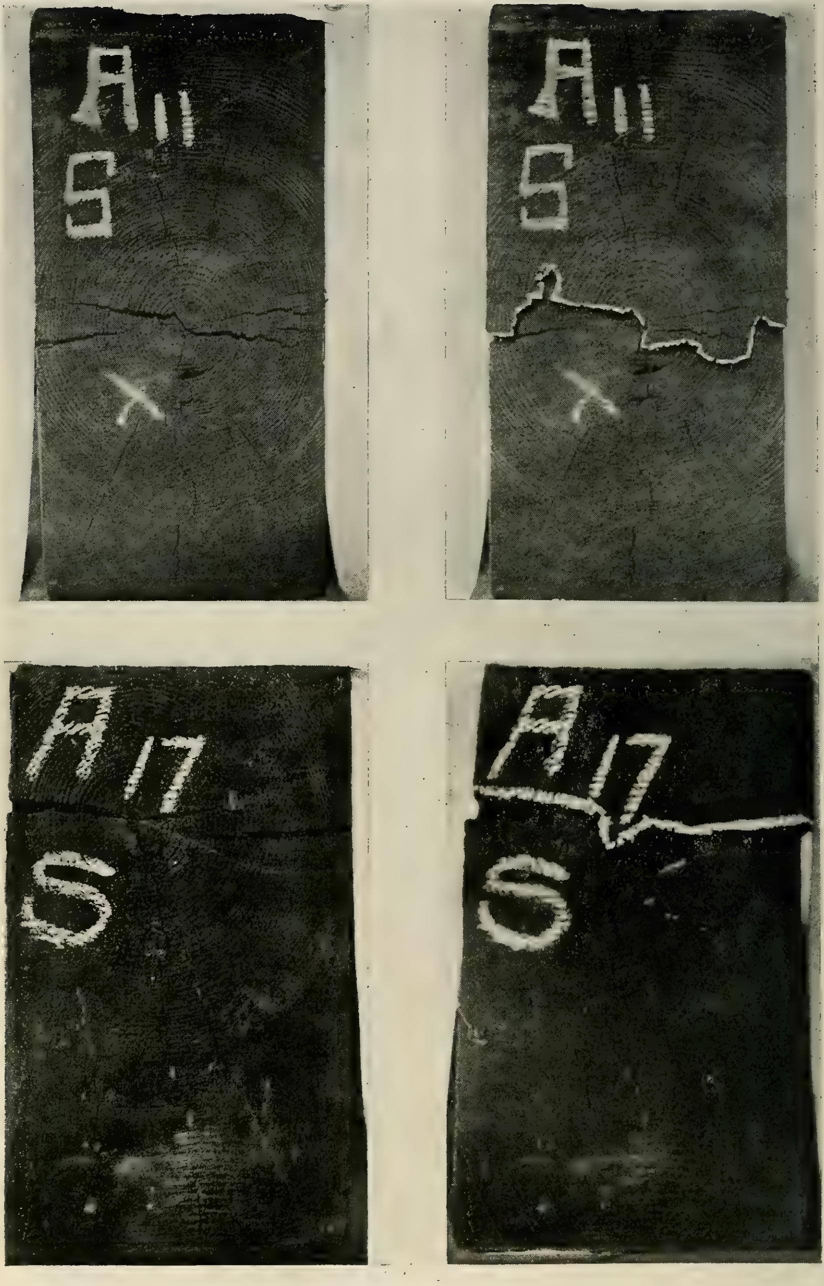


PLATE 10. VIEWS OF ENDS OF BEAMS BEFORE AND AFTER FAILURE.



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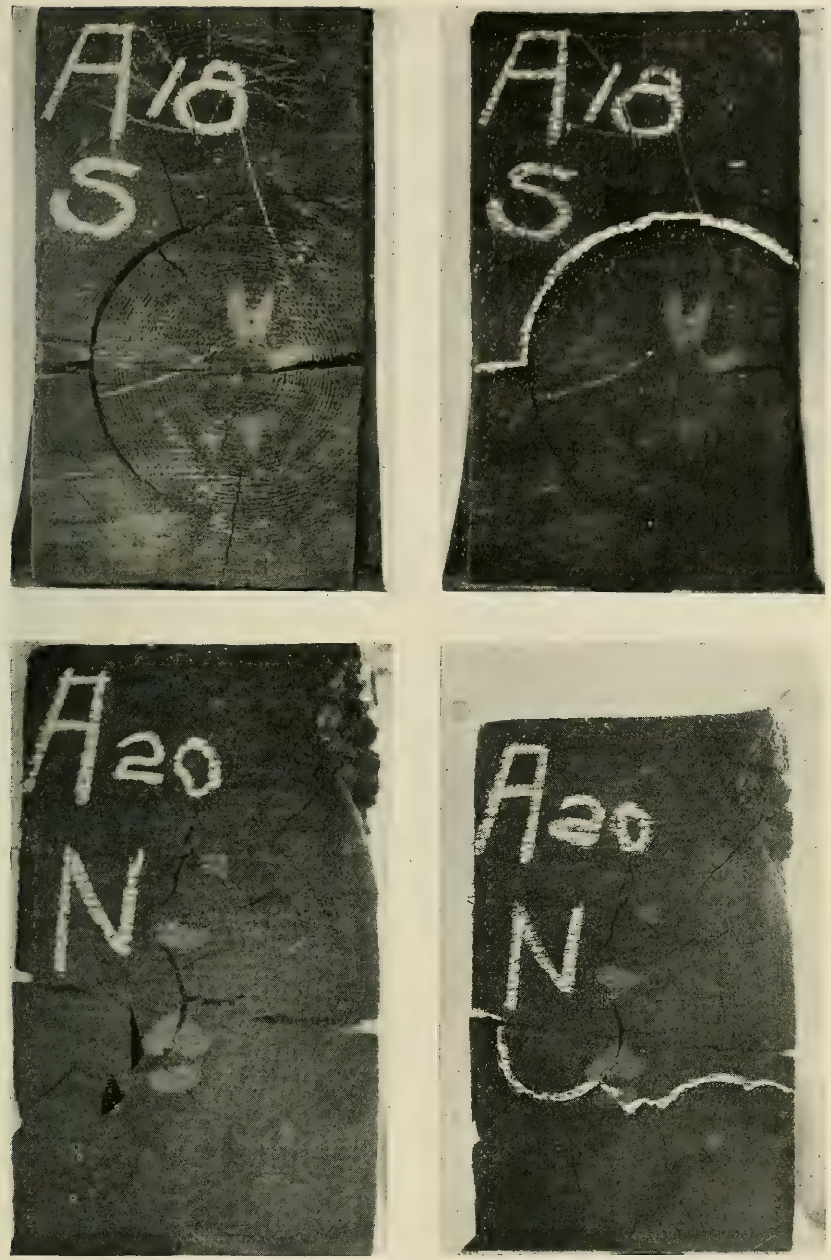


PLATE 12. VIEWS OF ENDS OF BEAMS BEFORE AND AFTER FAILURE.

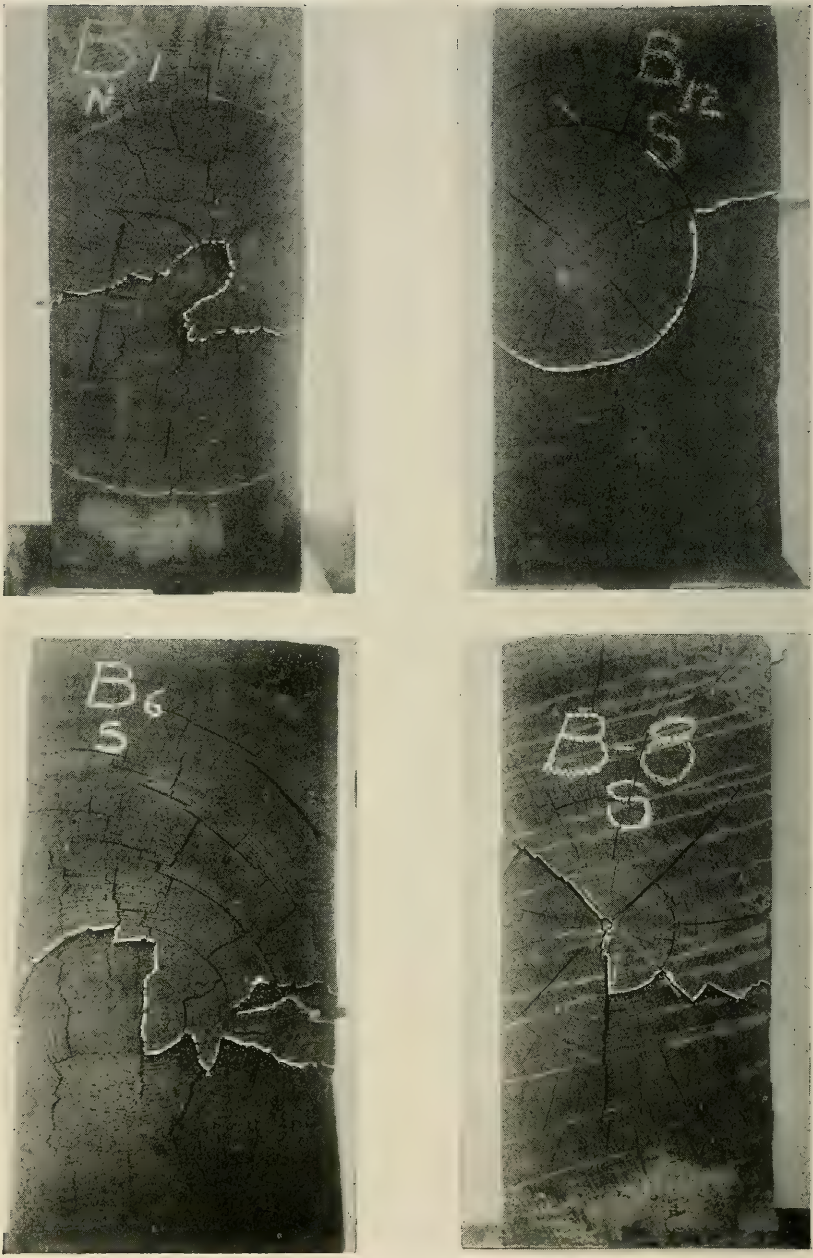
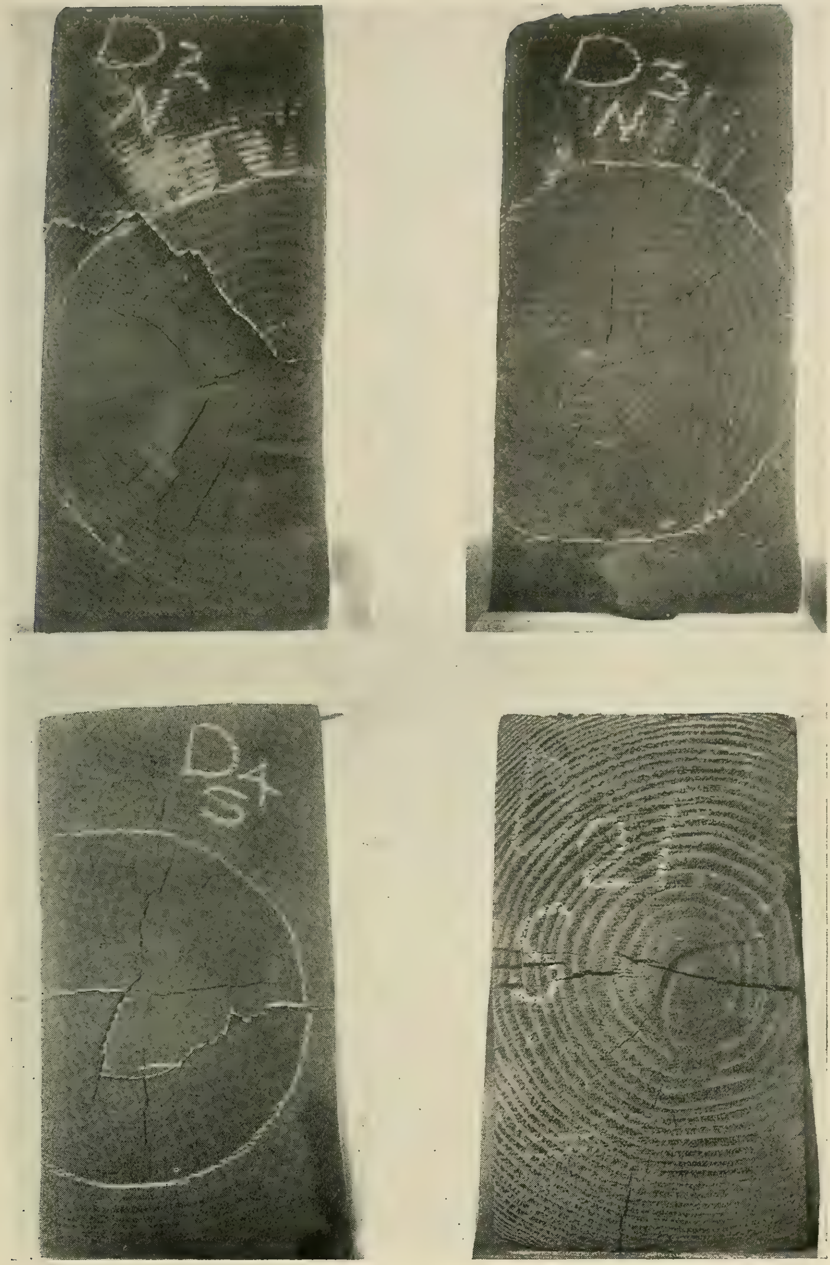


Plate 13. Views of Ends of Beams after Failure.



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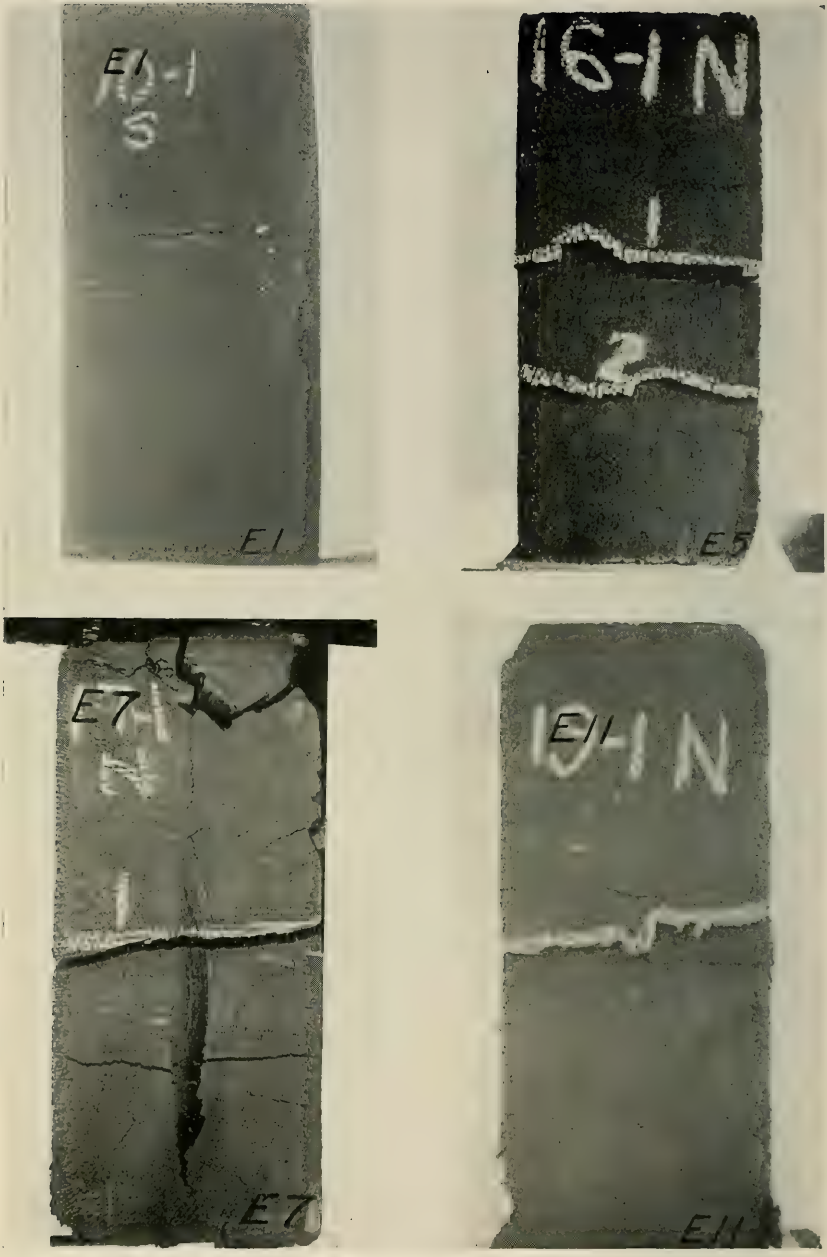

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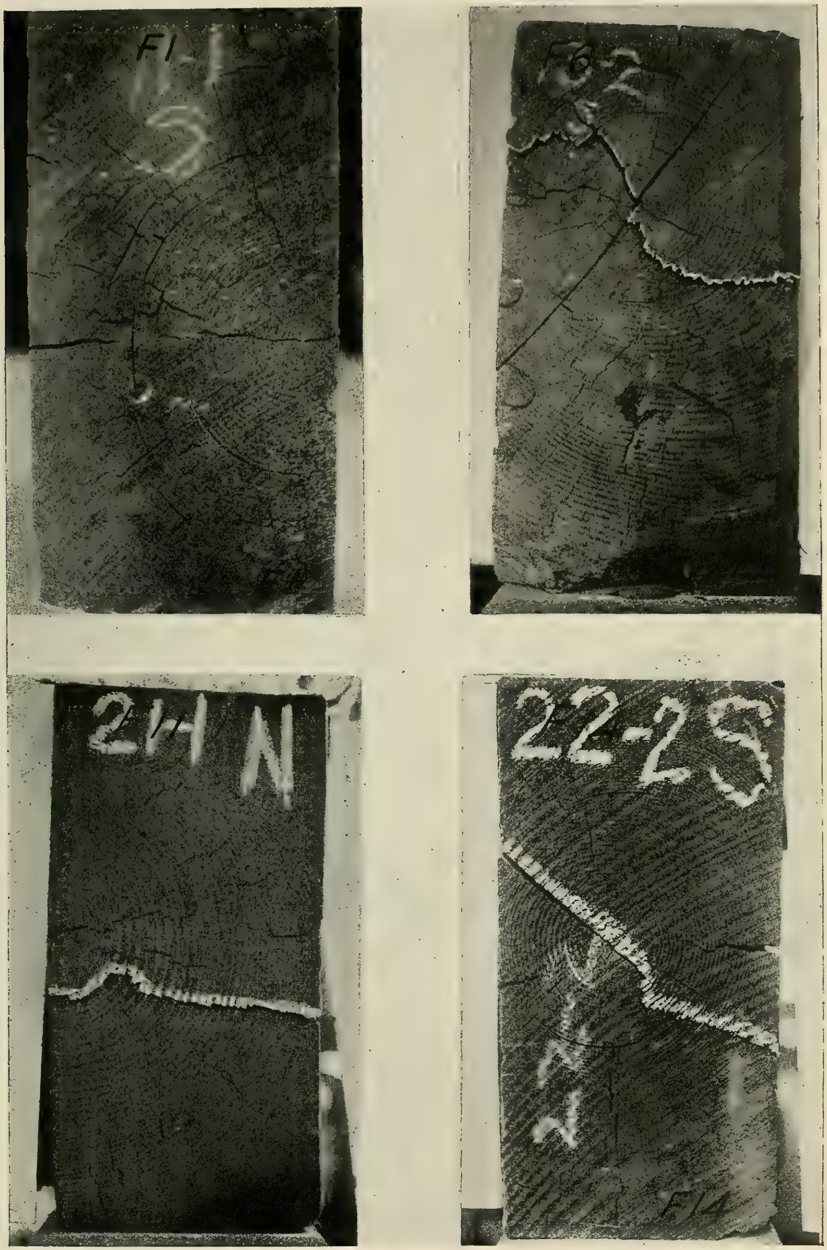

PLATE 16. VIEWS OF ENDS OF BEAMS BEFORE AND AFTER FAILURE.

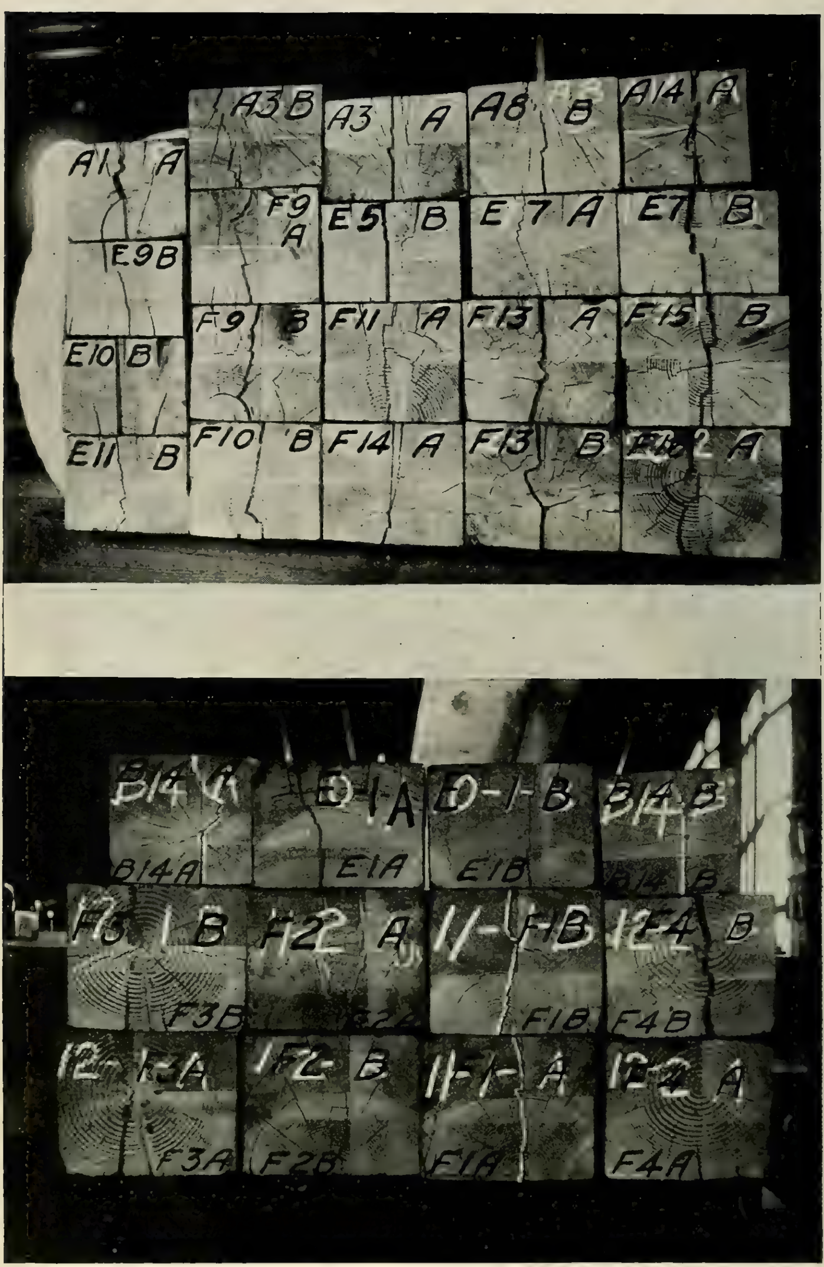

PLATE 17. VIEWS OF SHEAR BLOCKS AFTER FAILURE.

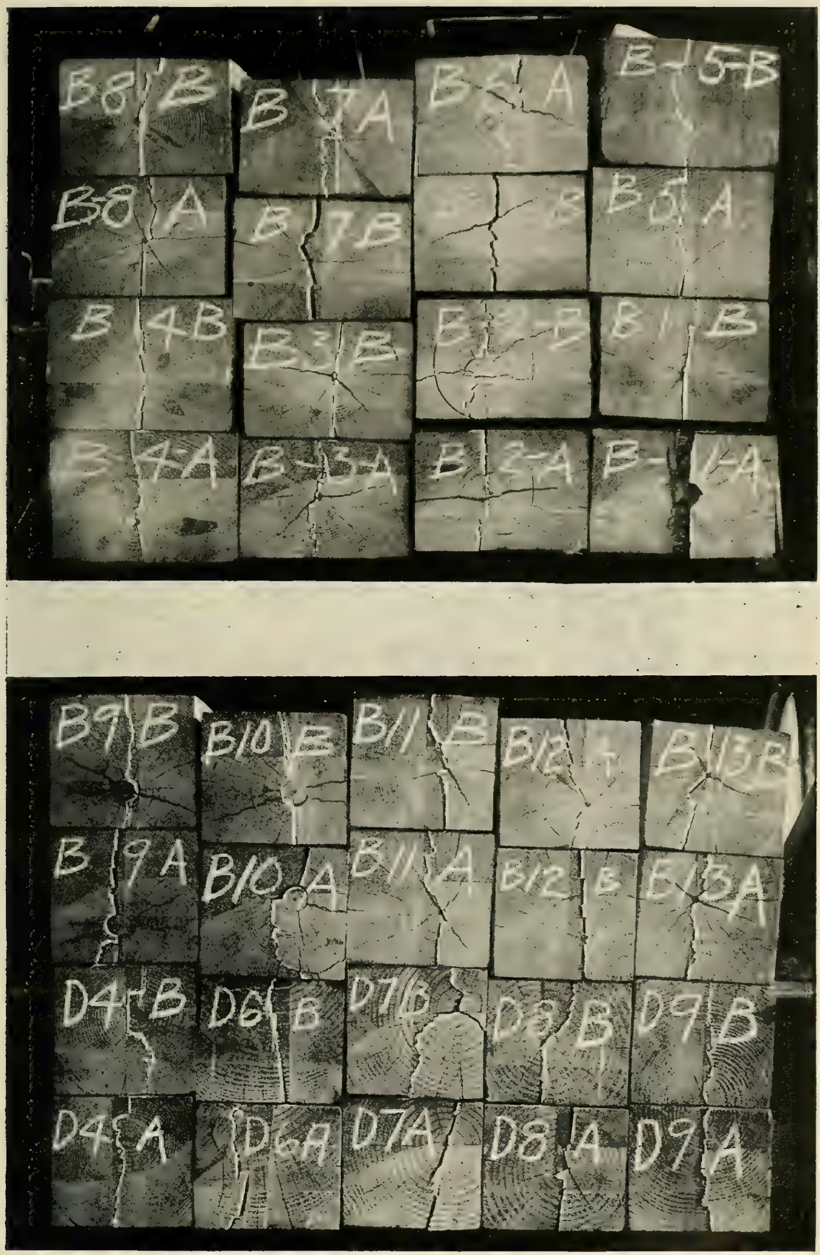

PLATE 18. VIEWS OF SHEAR BLOCKS AFTER FAILURE.

UNIVERSITY OF ILLINOIS
ENGINEERING EXPERIMENT STATION

BULLETIN NO. 41 DECEMBER 1909

TESTS OF TIMBER BEAMS

BY ARTHUR N. TALBOT, PROFESSOR OF MUNICIPAL AND SANITARY
ENGINEERING AND IN CHARGE OF THEORETICAL
AND APPLIED MECHANICS

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TESTS OF TIMBER BEAMS.

I. Introduction.

1. *Preliminary.*—Although timber has long been an important structural material, it is recognized that our knowledge of its structural properties is still quite inadequate, even though the work of recent years has added much valuable information. Generally speaking, the values for the strength of the various species of wood given in engineering text-books have been based on tests of small pieces taken from what may be considered to be selected wood, and until recently the number of tests on sticks of structural sizes has been very small. In view of the growing scarcity of timber and the necessity of utilizing the poorer grades, as well as because the competition with other structural materials is increasing, it would seem that the need for fuller information on the structural properties of timber is a matter of importance. It was with the view of adding data on the properties of timber in the form of stringers as used in many railroad structures and of the quality which may be expected to be found under the ordinary methods of purchase by railroad companies and others that this series of tests was undertaken.

The timber stringers were 8 x 16 in. x 15 ft. to 7 x 12 in. x 14 ft. in size. One hundred and twelve sticks were tested. The woods included longleaf pine, shortleaf pine, loblolly pine, and Douglas fir. A number of creosoted pine stringers were among those tested. The stringers were tested as beams with the load applied equally at the one-third points of the span length. The dimensions of the sticks were such as to bring out the strength of timber in horizontal shear. The influence of such defects as knots, seasoning checks, and wind shakes may be seen in the results. Minor test pieces were cut from the stringers and their flexural and shearing strength determined, and the relation of the properties of the smaller test pieces to the full-size stringers may be studied. It will be seen that the data of the tests have a bearing upon the properties of timber stringers under the conditions of ordinary purchase and practical service.

2. *Acknowledgment.*—The tests were made possible through the co-operation of the Illinois Central Railroad Company, and the Chicago, Rock Island and Pacific Railroad Company, which furnished the stringers. Mr. R. E. Gaut, Engineer of Bridges, and Mr. E. H. Bowser, Chief Timber Inspector, of the Illinois Central Railroad, were instrumental in selecting and providing the pine timber, and acknowledgment is made of their interest and helpfulness. Mr. J. B. Berry, Chief Engineer, Chicago, Rock Island and Pacific Railroad, furnished the fir stringers for these tests. The tests were carried on as work of the Engineering Experiment Station. Mr. W. R. Robinson has given helpful assistance in putting the results into form.

3. *Notes on Timber Testing.*—As already stated, the values for the strength properties of timber most generally cited in text-books and pocket-books in the past were evidently determined from small selected sticks. One text-book gives the strength of yellow pine in tension as 15 000 lb. per sq. in., in compression 9000 lb. per sq. in., and in longitudinal shear 500 lb. per sq. in. An engineers' pocket-book gives the value of the modulus of rupture of yellow pine as 15 300 lb. per sq. in. Lanza* cites several authorities as giving mean values of the modulus of rupture of yellow pine from 9000 to 15 000 lb. per sq. in., but the results of his own tests he reports as averaging 7500 lb. per sq. in. for modulus of rupture and 224 lb. per sq. in. for longitudinal shear and he very emphatically shows that the strength of commercial timber is much lower than usually quoted. Johnson* gives for yellow pine 9000 lb. per sq. in. in compression, 13 000 lb. per sq. in. in cross breaking and 600 lb. per sq. in. in longitudinal shear, while for loblolly pine, values of the corresponding strengths are 7000, 10 000, and 400 lb. per sq. in. The handbook of the Southern Lumber Manufacturers' Association (1904) gives for longleaf pine the following strengths: tension 15 200 lb. per sq. in., compression 6850 lb. per sq. in., cross breaking 10 900 lb. per sq. in., longitudinal shear 706 lb. per sq. in.; for shortleaf pine the corresponding values are 13 400, 5900, 9230, and 688; and for loblolly pine 14 400, 6500, 10 100, and 690. These values are stated to be based upon 15% moisture content on beams from which defective pieces were excluded and to give fairly well the range of strength of commercial timber. With such illustrations as these in mind, it

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*Applied Mechanics, by G. Lanza. The Materials of Construction, by J. B. Johnson.

does not seem strange that engineers may hold to higher values for the strength of commercial timber than later tests have shown to be tenable. A comparison of the foregoing values with the tests herein recorded shows that these tests gave strengths much lower than the values which are commonly cited.

The tests made on full-size pieces (structural sizes) have shown that the defects commonly found in commercial timber have a considerable influence on their strength, and it seems reasonable to expect that tests should be made on sticks of the size which is to be used and that the sticks should be selected in a manner similar to the way in which they will be chosen in the market, if it is desired to establish their strength under commercial conditions. Some of the earlier tests on so-called full-size sticks were not on structural sizes, but a number of series of tests on large sticks have been conducted which gave valuable information. The tests conducted by the Division of Forestry under the direction of Professor Johnson are reported in U. S. Forestry Circulars No. 12 and 15. Professor Lanza's extensive series of tests includes important and valuable data; the report of these may be found in Lanza's Applied Mechanics. The more recent work of the Bureau of Forestry on large-size beams under the general direction of Professor Hatt has also given valuable information. This is reported in the circulars of the Forest Service. An important series of tests on white pine beams by Onward Bates, reported in the Transactions of the American Society of Civil Engineers, vol. 23, may also be mentioned.

A valuable bibliography of timber tests and of the properties of timber may be found in Transactions of the American Society of Civil Engineers, vol. 54, part F, page 87. Important discussions of the subject of timber and timber tests may also be found in the same volume and in vol. 51. Bulletin No. 12 of the Division of Forestry, U. S. Department of Agriculture, gives valuable discussions on the strength and working strength for application to timber trestles. Valuable matter is to be found in the bulletins of the American Railway Engineering and Maintenance of Way Association. In Bulletin No. 85* of this association Professor Hatt gives the results of the recent work on timber tests of the Forest Service. In Bulletin No. 107* of the same association, the

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* See also Proceedings of American Railway Engineering and Maintenance of Way Association, vol. 8, pp. 409 and 417, and vol. 10, p. 533.

Committee on Wooden Bridges and Trestles reports important data on the properties of timber and on the practice of the railroads of the country.

4. *Formulas and Properties.*—The analysis on which the usual formulas for beams are based assumes a homogeneous material and a constant modulus of elasticity. These assumptions are fairly well met in such a material as steel within its elastic limit. Timber is not so uniform and homogeneous. The usual conception of a homogeneous bundle of fibers parallel with each other throughout the length of the beam is not entirely correct. The wood differs in different parts of the section,—heart wood and sap wood differ in their proportions and their distribution, even in different sticks of the same species (Fig. 1). As the sap wood and the heart wood are of different degrees of stiffness and as the relative amount of spring wood and summer wood varies also, it is apparent that the modulus of elasticity of the material will vary in different parts of a section and also that it will vary from section to section of the beam. The condition of the grain will also affect the action of the beam; thus the presence of cross grain will modify the distribution of the internal stresses. Presence of knots may change the position of the neutral axis as well as reduce the amount of effective fibers available for flexural strength. All such variations produce a distribution and an amount of stress which differ from the results obtained by ordinary beam analysis. An important feature in the strength of timber is that its resistance to longitudinal or horizontal shear is relatively low even in good timber. The presence of shakes and seasoning checks reduces the horizontal shearing strength and modifies the distribu-

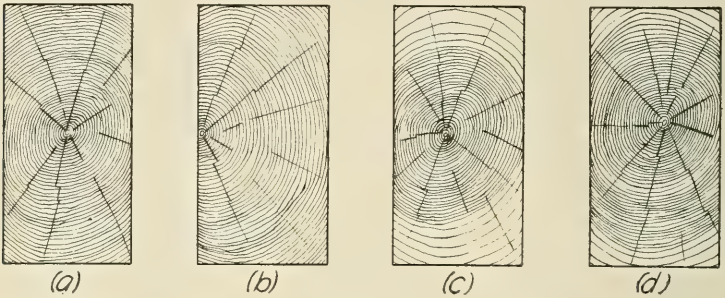

FIG 1. DISTRIBUTION OF HEARTWOOD AND SAPWOOD OVER SECTION.

tion of the stresses over the section. It seems evident, then, (a) that the ordinary formulas when applied to timber must be considered to be largely empirical; and (b) that tests of full-size sticks are necessary to obtain working values for the timber used.

The derivation of the usual formulas for beams may be found in the standard text-books on mechanics of materials. The ordinary formula for resisting moment for a beam of rectangular cross-section is

$$M = \tfrac{1}{6} fbd^2 \quad \dots\dots\dots\dots\dots\dots\dots (1)$$

where f is the unit-stress or fiber stress at the top or bottom of the section, b is the width of the beam, and d its depth. In the principal tests herein described, the load was applied equally at the one-third points of the span length, and the maximum bending moment due to the applied load is therefore $\frac{1}{6} Wl$, where W is the total load applied and l is the span length. The formula for the deflection at the center of a beam loaded at the one-third points is $\frac{23}{1296} \frac{Wl^3}{EI}$, where E is the modulus of elasticity applicable to flexure and I is the moment of inertia of the cross-section. In these formulas the effect of the deformations produced by horizontal shear is not taken into consideration.

In the discussion of shearing stresses, it should be noted, to begin with, that the intensity of the shearing stress at any point in a section (i. e., the shearing unit-stress) is the same for the vertical shear and for the horizontal shear. The formula for the vertical shearing unit-stress at the neutral axis and also for its equal, the horizontal or longitudinal shearing unit-stress at the same point, is

$$v_0 = \frac{3}{2} \frac{V}{bd} \quad \dots\dots\dots\dots\dots\dots\dots (2)$$

where V is the total external vertical shear on the given section. In the case of the manner of loading above referred to, if we neglect the weight of the beam, the external vertical shear V is constant from the support to the load point and equal to one-half of the load; and it is zero between the load points.

Above and below the neutral axis the vertical shearing unit-stress, and therefore the horizontal shearing unit-stress, is given by the formula

$$v = \frac{3}{2} \frac{V}{bd} \left[1 - \left(\frac{z}{\frac{1}{2}d}\right)^2\right] = v_0 \left[1 - \left(\frac{z}{\frac{1}{2}d}\right)^2\right] \quad \dots\dots\dots (3)$$

where z is the distance above or below the neutral axis. The variation of the intensity of the shearing stress throughout a vertical section (applicable to both vertical and horizontal shearing stress) is illustrated in Fig. 2(a). It is seen that the decrease in stress is not very great over the middle third of the depth of the beam.

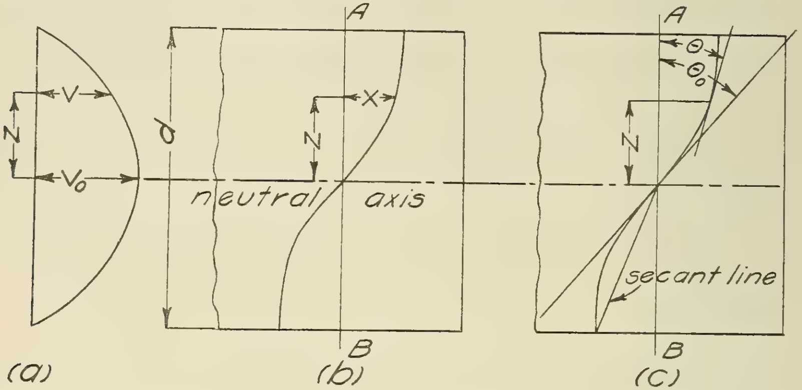

FIG. 2. DISTRIBUTION OF SHEARING STRESS AND MOVEMENT OF FIBER DUE TO HORIZONTAL SHEAR.

For convenience and conciseness of expression, the term fiber stress will be used in this bulletin to mean the calculated compressive or tensile unit-stress at the top or bottom of the beam for a section having the maximum bending moment, denoted by f in equation (1). The term elastic limit will be used to mean the calculated fiber stress at the elastic limit. The term horizontal shearing stress will be used to mean the shearing unit-stress at the neutral axis, v_0, for a section having the maximum external vertical shear. Further, the formulas will be used beyond the elastic limit of the beams, where they give apparent or empirical values of the stresses.

An effect of horizontal shearing stress is to cause a distortion of the section from a straight-line section, as though the fibers had moved longitudinally. In a material like timber in which the modulus of elasticity against longitudinal shear is relatively small, this movement may be expected to be greater than in a homogeneous material or in one having a higher modulus of elasticity. Although the resistance to shear prevents the sliding which occurs when several boards are piled one above another and flexure applied, yet a vertical line drawn across a beam will be found to vary from a straight line after a load is applied. If, now, the beam fails by horizontal shear the upper portion of the beam at the end will project beyond the lower as shown in the beams in Plate 7 (frontispiece), and the failure will extend some distance along the length of the beam.

It may be shown that the amount of the horizontal movement x of a point on the beam with reference to a straight line, (see Fig. 2 (b), the line of reference AB considered to remain normal to the elastic curve at the neutral axis), is given by the equation

$$x = \frac{3}{2}\frac{V}{bdE}\left[z - \frac{1}{3}\frac{z^3}{(\frac{1}{2}d)^2}\right] = \frac{v_0 z}{E}\left[1 - \frac{1}{3}\left(\frac{z}{\frac{1}{2}d}\right)^2\right] \ldots\ldots (4)$$

where E is the modulus of elasticity for horizontal shear and z is the distance of the point from the neutral axis. It may be noted that this E is much smaller in timber than the E used in the formula for determining the deflection of beams. The form which a section takes with reference to the normal to the elastic curve is shown by the curve in Fig. 2 (b). The total longitudinal movement of a point at the top with reference to a point at the bottom is, by the foregoing formula, $\frac{2}{3}\frac{v_0 d}{E}$. The slope which the curve at any point makes with the normal already referred to (Fig. 2 (c)), is given by the equation

$$\tan \Theta = \frac{v}{E} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5)$$

where Θ is the slope of the curve with the reference line, and v is the unit-shear at the same point. For a point at the neutral axis the slope of the curve is $\tan \Theta_0 = \frac{v_0}{E}$. At the top and bottom the direction of the curve is parallel with the reference line. The slope of the secant line through the top and bottom of the curve is approximately two-thirds of the slope of the curve at the neutral axis, since for small angles the tangent and angle are equal. The value of E for horizontal shear applicable in these formulas has not been established so far as known. It is evident that the total amount of horizontal movement in the stringer of ordinary size is very small.

It may be anticipated that the properties of timber lack uniformity and that for any given grade or kind of timber they will vary considerably with the individual stick. Tests may be expected to be of service in getting a range of results, in finding methods of failure most likely to occur, and in indicating what to look out for in service.

II. Test Pieces and Method of Testing.

5. *The Timber Stringer Series.*—The tests of full-size timber stringers for convenience of discussion are classified in six series: A, B, C, D, E, and F. These series are not expressive of divisions of the investigation, but were adopted during the development of the work. Table 1 gives data of the materials, size of sticks, condition of the timber, etc. The sticks were generally 14 ft. long, though the fir stringers came in lengths of 32 ft. Obstacles in the way of shipment and of making tests immediately upon receipt of the timber rendered it impracticable to carry out the original plan in every way and not all the conditions and determinations first planned were included in the final tests. The first tests (Series C, tested 1905-6) were made to give a comparison of the properties of creosoted and untreated timber of shortleaf pine and loblolly pine under the conditions of treatment then in use by the Illinois Central Railroad. The details of the treatment and the

TABLE 1.

Classification of Timber Stringers.

Series	Wood	No. of Pieces	Condition	Nominal Size in. x in. x ft.	Seasoning months
C	Shortleaf pine	4	Untreated	7 x 16 x 14	12
C	Shortleaf pine	4	Creosoted	7 x 16 x 14	10*
C	Shortleaf pine	4	Creosoted	7 x 16 x 14	10*
C	Loblolly pine	4	Untreated	7 x 16 x 14	12
C	Loblolly pine	4	Creosoted	7 x 16 x 14	10*
C	Loblolly pine	4	Creosoted	7 x 16 x 14	10*
A	Longleaf pine	8	Untreated	7 x 16 x 14	18
A	Longleaf pine	6	Untreated	7 x 14 x 14	18
A	Longleaf pine	6	Untreated	7 x 12 x 14	12
B	Longleaf pine	8	Untreated	7 x 16 x 14	4
B	Longleaf pine	6	Untreated	7 x 14 x 14	4
D	Loblolly pine	8	Untreated	7 x 16 x 14	6
D	Loblolly pine	6	Creosoted	7 x 16 x 14	2*
D	Loblolly pine	6	Untreated	7 x 14 x 14	6
D	Loblolly pine	6	Creosoted	7 x 14 x 14	2*
E	Old Douglas fir	12	Untreated	7 x 16 x 15	11 years
F	New Douglas fir	16	Untreated	8 x 16 x 15	Partly seasoned

*Time of seasoning at treatment. Creosoted beams of Series C were tested about two months after treatment; those of Series D seven months after treatment.

amount of oil used are given in Table 2. The amount of the horizontal shearing strength developed in the many beams failing by horizontal shear in this series was so small that it was thought best to make tests on beams of several depths to find whether a smaller depth of beam would permit the full value of the modulus of rupture of the wood to be developed. At the same time the effect of pronounced seasoning checks and of large knots was taken up and also a further comparison of treated and untreated loblolly pine. These stringers, furnished by the Illinois Central Railroad, and tested in July and August, 1906, December, 1906, and January, 1907, are included in Series A, B, and D. Two conditions of seasoning were included in the longleaf pine stringers,—one a period of about 18 months in Series A and the other one of about 4 months in Series B. Series E and F comprised Douglas fir stringers furnished by the Chicago, Rock Island and Pacific Railway. The stringers in Series E had seen service for 11 years in a trestle in Nebraska and this series may be expected to represent the degree of seasoning and seasoning checks attained by such wood in service. This timber was as well seasoned as may be expected under ordinary atmospheric conditions. Series F was unused Douglas fir stringers partly seasoned and may be expected to represent the condition of such timber when first put into service. Although no relation between the quality of the wood in the two sets of stringers is known, the results will furnish some comparison between the properties of such stringers under two sets of conditions. These fir stringers came in lengths of 32 ft. and

TABLE 2.

Data of Treatment of Timber.

Designation	Steam		Vacuum		Creosote			
	Time hr. min.	lb. per sq. in.	Time hr. min.	Inches	Time hr. min.	lb. per sq. in.	Temp. F.	lb. per cu. ft.
C 5—C 8	4 30	35	2 00	24.5	0 25	88	170°	6.2
C 9—C 12	4 30	35	2 00	24.5	2 00	100		7.9
C 17—C 20	4 30	35	2 00	24.5	0 25	88	170°	17.5
C 21—C 24	4 30	35	2 00	24.5	2 00	100		14.9
D 15—D 26	5 00	30	2 00	24	1 30	125		16.0
M 3 x 3 in.	5 00	30	2 00	24	1 30	125		20.3
M shear	5 00	30	2 00	24	1 30	125		10.6
N 3 x 3 in.	5 00	30	2 00	24	1 30	125		17.2
N shear	5 00	30	2 00	24	1 30	125		19.3

were cut in two before testing. In the designation, an odd number and the succeeding even number represent two pieces from one stick. In Series A, B, and D, a few sticks had been selected having knots of such size and in such a position that these defects would, in any thorough-going inspection, have been cause for rejection. These were included with a view of finding the effect of such marked defects. The shallower stringers in Series A, B, and D were cut down from 16-in. sticks.

In Table 1 the time of seasoning of the untreated stringers at test is given. The stringers were in general left in the yard until shipment and upon reaching the laboratory were piled and stored in such a way that they continued to season slowly. For the creosoted sticks the time of seasoning at treatment is given in Table 1. It is not expected that the time which elapsed after treatment affected in any marked way the properties of the wood. As already stated, the old Douglas fir stringers were well seasoned. As noted further on, the results of the moisture determinations are given in Table 4 and the method of determination is described under "8. Moisture Determination."

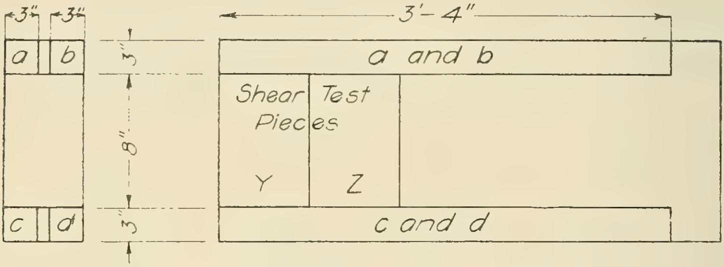

FIG. 3. LOCATION OF MINOR TEST PIECES IN FULL-SIZE STRINGERS.

6. *Minor Test Pieces.*—After the cross-bending test of the full-size sticks had been made, minor test pieces were cut from the stringers in Series A, B, D, E, and F for further test. These minor test pieces included shear test pieces and small test beams. The classification of the minor test pieces is given in Table 3. The position of these test pieces in the stringer and their designation are shown in Fig. 3. The shear test pieces (y and z, Fig. 3.) were taken from near the middle of the depth of the stringer. If the stringer had failed in horizontal shear at one end, the shear test piece was cut from the other end. The shear test piece was the full thickness of the stringer and about 8 to 10 in. wide and

12 in. long. It was cut so as not to contain knots, but it did include seasoning checks which existed in the middle half of the depth of the stringer and as such is more nearly representative of the shearing strength of the full-size stick than are the small test pieces which have generally been used hitherto in the determination of shearing strength. One hundred and fifty-five of these shear test pieces from Series A, B, D, E, and F were tested. The minor test beams, (a, b, c, and d, Fig. 3), of which there were three hundred and eleven, were cut from the four corners of one end of the stick. These pieces were usually 3 x 3 x 40 in. and were tested with a span of 36 in. They were sawed out and tested to give a comparison of the strength in cross bending of the wood at the top and bottom of the stringer with the strength developed in the full-size stick.

TABLE 3.

Classification of Minor Test Pieces.

These test pieces were cut from the tested stringers.

The small test beams were 3 x 3 x 40 in. The shear blocks were 7 x 10 x 12 in.

Series	Wood	Test Pieces	No. of Pieces	Condition	Seasoning months
A	Longleaf pine	Beam	80	Untreated	18
A	Longleaf pine	Shear block	33	Untreated	18
B	Longleaf pine	Beam	51	Untreated	4
B	Longleaf pine	Shear block	28	Untreated	4
D	Loblolly pine	Beam	50	Untreated	6
D	Loblolly pine	Shear block	26	Untreated	6
D	Loblolly pine	Beam	47	Creosoted	2
D	Loblolly pine	Shear block	22	Creosoted	2
E	Old Douglas fir	Beam	47	Untreated	11 years
E	Old Douglas fir	Shear block	26	Untreated	11 years
F	New Douglas fir	Beam	46	Untreated	Partly
F	New Douglas fir	Shear block	20	Untreated	seasoned

7. *Miscellaneous Test Pieces. Series M and N.*—Several stringers were cut up at the mill as shown in Fig. 4. In series M, all pieces were creosoted. In Series N (cut from 16-ft. stringers), the alternate pieces were treated by the creosoting process (the even numbers are creosoted and the odd numbers untreated). The statement of treatment is given in Table 2. The 4 x 4 x 42 in. pieces were cut to 3 x 3 x 40 in., and were tested as beams in the same way (usually 36-in. span) as were the small beams of the series of

minor test pieces. The shear test pieces were approximately 7 x 8 x 12 in. The creosoted pieces had been cut about three months at time of treatment and the untreated pieces about twelve months at time of test. One hundred and four shear blocks and 122 small test beams were tested in series M and N.

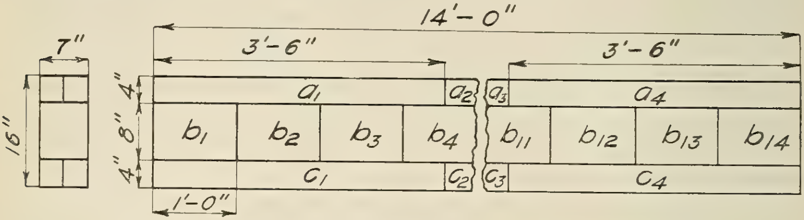

FIG. 4. LOCATION OF MISCELLANEOUS TEST PIECES.

8. *Moisture Determination.*—From each stringer after test a disc about 1 in. thick and the full cross-section of the stringer was cut about 4 ft. from one end. These discs were weighed immediately and then thoroughly dried in an oven at a temperature of about 180° F. for 24 hours, or more, until the loss of weight for the last 6 hours was less than 1 %. The results are given in Table 4. The moisture is unevenly distributed in a stick, varying throughout the length and section, but the results may be taken as indicative in a general way of the moisture condition of the sticks. Determinations were not made for Series C, M, and N.

9. *Cross-bending Tests of Stringers.*—The stringers were tested in cross bending on a 200 000-lb. Olsen beam-testing machine in the Laboratory of Applied Mechanics of the University of Illinois. The span was 13 ft. 6 in. except in Series E and F where it was 14 ft. 6 in. The beams rested on rocker supports which gave free longitudinal movement. Iron bearing plates 8 in. wide, 1 in. thick, and of a length greater than the width of the stringer were used to prevent the crushing of the wood at the supports. The load was applied equally at two points on the top of the beam, each one third the span length from the supports. Bearing plates like those before mentioned were used at the points of application of the load. The load was applied progressively to failure, a stop being made at the various loads to give the observers time to read the instruments. The head of the testing machine was run down at a speed of 0.17 in. per minute. This movement corresponds to an application of longitudinal or fiber deformation in

the extreme fiber at mid-span equal to 0.00056 in. per inch of length per minute for a 7 x 16-in. beam and 13½ ft. span.

TABLE 4.

MOISTURE CONTENT OF TEST PIECES.

Series A		Series B		Series D		Series D		Series E		Series F	
Des.	percent	Des.	percent	Des.	percent	Des.	percent	Des.	percent	Des.	percent
A 1	19.7	B 1	26.6	D 1	21.9	D 15	39.3	E 1	14.9	F 1	24.9
A 2	18.6	B 2	27.2	D 2	46.8	D 16	33.8	E 2	17.4	F 2	23.6
A 3	18.5	B 3	27.0	D 3	45.2	D 17	31.4	E 3	14.1	F 3	23.8
A 4	18.8	B 4	25.4	D 4	30.0	D 18	30.9	E 4	14.4	F 4	24.0
A 5	18.9	B 5	25.2	D 5	....	D 19	31.9	E 5	16.8	F 5	23.9
A 6	18.9	B 6	25.3	D 6	41.0	D 20	36.9	E 6	16.8	F 6	25.9
A 7	18.1	B 7	27.8	D 7	28.2	D 21	29.0	E 7	15.7	F 7	22.0
A 8	18.5	B 8	25.5	D 8	45.7	D 22	51.1	E 8	16.3	F 8	23.2
A 9	18.4	B 9	22.6	D 9	71.1	D 23	22.1	E 9	17.0	F 9	22.1
A 10	18.3	B 10	29.1	D 10	26.2	D 24	51.6	E 10	17.5	F 10	23.2
A 11	19.5	B 11	29.1	D 11	31.2	D 25	42.0	E 11	16.8	F 11	22.7
A 12	19.0	B 12	26.2	D 12	60.0	D 26	33.0	E 12	17.9	F 12	26.8
A 13	18.3	B 13	30.2	D 13	41.4					F 13	25.4
A 14	19.5	B 14	25.0	D 14	25.2					F 14	22.8
A 15	19.4									F 15	23.5
A 16	20.2									F 16	24.5
A 17	19.7										
A 18	20.6										
A 19	16.9										
A 20	20.6										
Av.	19.0		26.6		39.5		36.1		16.3		23.9

The deflection of beam at mid-span was measured by means of a silk thread stretched between two nails set in the wood over each support at one-half the depth of the beam. A mirror and scale placed at the center of the beam permitted the deflection to be read to 0.01 in. The longitudinal or fiber deformation in the extreme fiber was read on the beams of Series C. On two of these the method used was quite similar to that commonly used for determining the neutral axis of reinforced concrete beams, except that the instruments were attached directly to the beam at the extreme fibers. Fig. 5 shows the arrangement of these. In two beams four Johnson extensometers were used and on the remainder only two, one at the top and the other at the bottom of the beam. A gauged length of 36 and of 40 inches was used. Acknowledgment is made to Mr. L. E. Moore for assistance in developing the deformation tests.

An effort was made to take measurements representative of the horizontal shearing slip or detrusion at the ends of the stringers. It was hoped that this method would give some information on the action of the horizontal shear and whether there was a shear elastic limit or yield point. The apparatus and methods were tentative and experimental and were not expected to give quantitative results. Two methods were used. In the method used in Series C, the first tried, (see Fig 6(a)) two pointers were fastened by screws to one side of the stringer over a support. On one pointer the screws were 12 in. apart, placed symmetrically with the center or neutral axis of the beam. On the other pointer the two screws were 2 in. apart and symmetrical with the center. Measurements were taken between two points at the upper ends of the pointers. The change in this measurement was due to the horizontal detrusion of the fibers. For the lever arms used, the horizontal movement from equation (5) may be expected to be about two-thirds of the observed reading. In the second method (see Fig. 6(b)) one pointer was fastened at points 12 in. apart as before and the other was secured by two screws in a horizontal line passing through the upper screw of the first pointer. The measurements were taken at the top as before. For the dimension used the horizontal movement would be one-third of the reading. Neither apparatus was fully satisfactory, but the experiments show that a satisfactory instrument may be devised for the purpose and the results found are instructive in several ways, although they are not sufficiently complete and consistent to warrant publication.

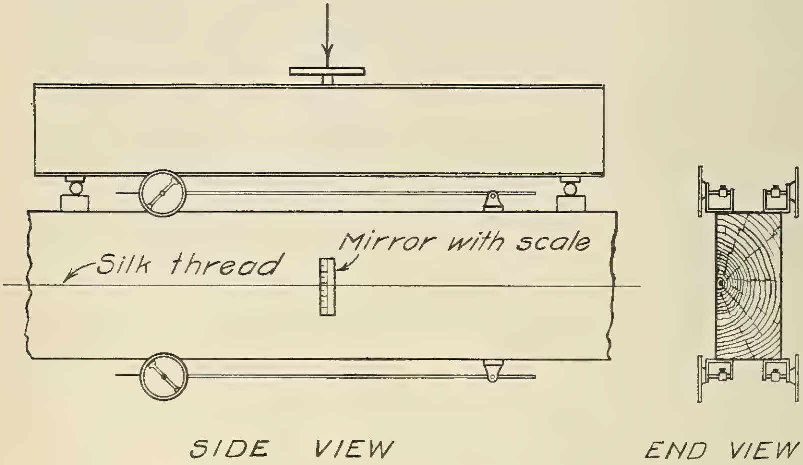

FIG. 5. LOCATION OF INSTRUMENTS.

10. *Shear Tests.*—In shear tests (see Fig. 7) the shear test block was placed in the testing machine with the grain vertical. A cast-iron plate was put under one-half of the piece and the opposite half at the top was covered with a similar plate. There was a space of perhaps $\frac{1}{4}$ to $\frac{1}{2}$ in. between the vertical lines passing through the edges of these two plates. The tendency of the block to slip sidewise as the load was applied was counteracted by putting supports between the test piece and the columns of the testing machine. The speed of the machine in these tests was 0.17 in. per minute.

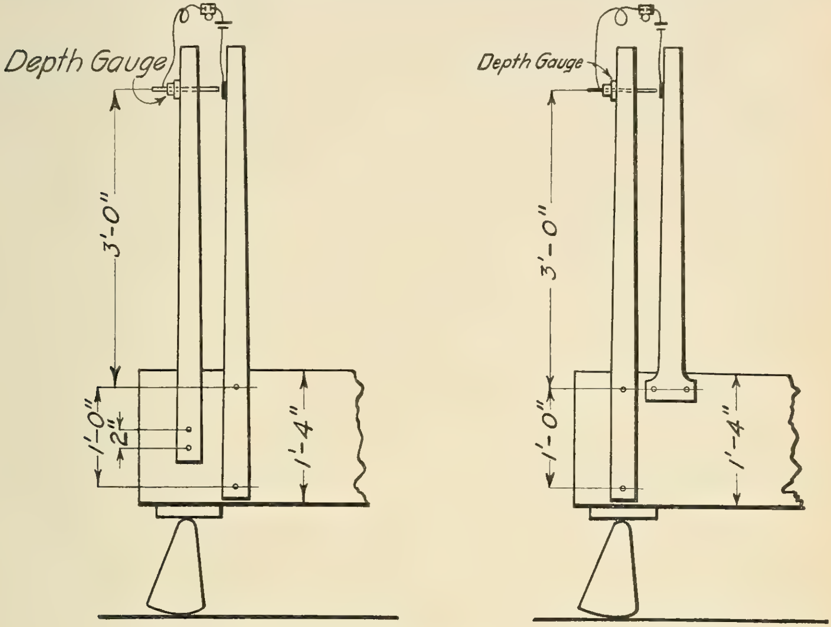

FIG. 6a AND 6b. APPARATUS FOR MEASURING LONGITUDINAL SHEAR MOVEMENT.

11. *Tests of Small Test Beams.*—The small test beams of the minor and the miscellaneous series were tested generally with a span of 36 in. and the load was applied equally at the one-third points of the span. Care was taken to permit longitudinal movement of the supports as the load was applied. The deflection was measured by a deflectometer with the contact point placed under the center of the beam. A speed of 0.3 in. per minute was used.

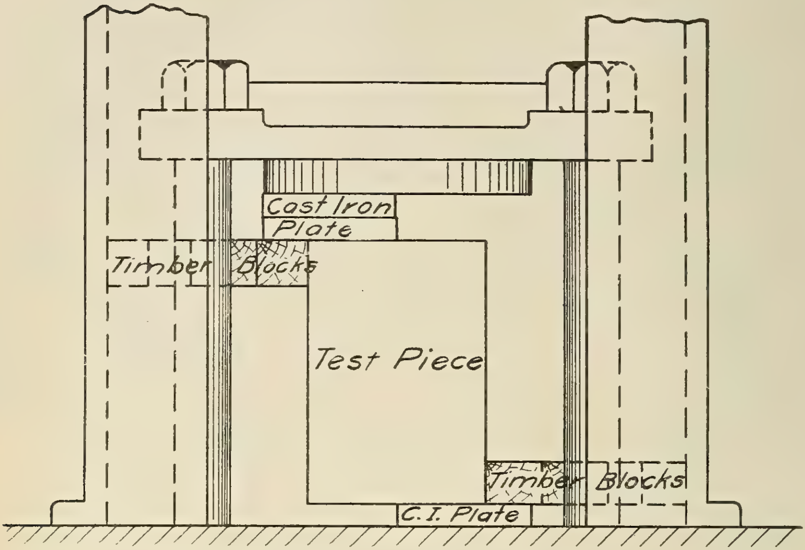

FIG. 7. SHEAR TEST APPARATUS.

III. EXPERIMENTAL DATA AND DISCUSSION.

12. *Stringer Test Data.*—In Tables 5 to 12 are given data for the full-size stringers and their tests as beams in Series A, B, C, D, E, and F. The tables on the left hand pages include a general description of the beams, and the companion tables on the opposite pages give results of the test. The elastic limit was determined from the deflection diagrams by finding the point at which the deflection increases markedly more rapidly than the load. In some cases this involves exercise of judgment. The values so found are somewhat smaller than those which would be obtained by finding the point at which the slope of the curve is 50% greater than the general slope at lower loads. The stress in outer fiber both at the elastic limit and at failure was calculated by using the usual formula (equation (1) p. 7), $M = \frac{1}{6} fbd^2$. The horizontal shearing stress at the neutral axis was calculated by the formula (equation (2) p. 7) $v_0 = \frac{3}{2}\frac{V}{bd}$, where V is the total vertical shear at the sec-

tion considered. In the column headed "Manner of Failure" is given the general way in which failure occurred.

13. *Views and Load-deflection Diagrams.*—The views in Plates 1 to 18 given in the frontispiece are from photographs. They were selected to show representative failures in shear, tension, and compression. In a number of cases the end of the beam before failure and after failure is shown. The difference in appearance in the two ends of the beam is also shown for one beam. The size and appearance of seasoning checks and their relation to the line of shear may be noted. Views of shear blocks are given in Plates 17 and 18. Reference may well be made to the views in following the discussion of the test.

The load-deflection diagrams for Series A, B, C, D, E, F, and N are given in Fig. 11 to 25 at the end of the text. The point selected as the elastic limit is marked on the diagrams.

14. *Phenomena of Tests.*—As the load was progressively applied the beams deflected more and more, and generally failure did not occur until after the elastic limit was passed. In some cases popping sounds were heard. The manner of failures may be classed as (1) tension, (2) compression, (3) horizontal shear. In the tension failure the beam generally failed suddenly by tension in the lower fiber, the crack extending into the beam some distance. In a few cases this tension crack was nearly vertical but there were more instances of cross-grain tension and a few of splintering tension. Beams failing in tension were much affected by the presence of knots and cross grain in the lower portion of the beam. The failures by compression in the upper fiber of the beam were slow and gradual and the load-deflection curves show characteristic features. These failures were generally in poor or brash wood. Seemingly the knots and cross grain had less effect on the compression side than on the tension side. The failures in horizontal shear were very sudden and generally no warning was given, though in a few cases considerable horizontal slip was shown by the instruments and in many cases the increased deflection shown on the deflection curves near the maximum load was probably due to the horizontal shearing movement. After the shear failure and before the head of the testing machine had been moved, the upper portion of the beam at the failed end projected over the lower portion $\frac{1}{4}$ in. or more. The stick continued to carry load, acting as two beams one on top of the other, and when the test

TABLE 5.

DATA OF BEAMS IN SERIES C.

Des.	Nominal Size in. x in. x ft.	Description	Condition
C 1	7 x 16 x 14	Shortleaf pine, untreated (a)	No important knots.
C 2	7 x 16 x 14	Shortleaf pine, untreated (a)	Large seasoning check.
C 3	7 x 16 x 14	Shortleaf pine, untreated (a)	Apparently good stick.
C 4	7 x 16 x 14	Shortleaf pine, untreated (a)	Apparently good stick.
C 5	7 x 16 x 14	Shortleaf pine, creosoted (b)	Apparently good stick.
C 6	7 x 16 x 14	Shortleaf pine, creosoted (b)	Apparently good stick.
C 7	7 x 16 x 14	Shortleaf pine, creosoted (b)	
C 8	7 x 16 x 14	Shortleaf pine, creosoted (b)	
C 9	7 x 16 x 14	Shortleaf pine, creosoted (b)	Slightly cross-grained.
C 10	7 x 16 x 14	Shortleaf pine, creosoted (b)	Cross-grained.
C 11	7 x 16 x 14	Shortleaf pine, creosoted (b)	Knot under south load point.
C 12	7 x 16 x 14	Shortleaf pine, creosoted (b)	Apparently good stick.
C 13	7 x 16 x 14	Loblolly pine, untreated (a)	
C 14	7 x 16 x 14	Loblolly pine, untreated (a)	Four knots under south load.
C 15	7 x 16 x 14	Loblolly pine, untreated (a)	
C 16	7 x 16 x 14	Loblolly pine, untreated (a)	
C 17	7 x 16 x 14	Loblolly pine, creosoted (b)	
C 18	7 x 16 x 14	Loblolly pine, creosoted (b)	
C 19	7 x 16 x 14	Loblolly pine, creosoted (b)	
C 20	7 x 16 x 14	Loblolly pine, creosoted (b)	
C 21	7 x 16 x 14	Loblolly pine, creosoted (b)	Knot under north load.
C 22	7 x 16 x 14	Loblolly pine, creosoted (b)	Knot under south load.
C 23	7 x 16 x 14	Loblolly pine, creosoted (b)	Cross-grained.
C 24	7 x 16 x 14	Loblolly pine, creosoted (b)	

(a) Seasoned 12 months, (b) Seasoned 10 months.

was carried to destruction the second failure was generally by tension and at a load considerably under that causing the shear failure, though in the case of A1, A15 and E 1 the maximum load was considerably above that causing the shear failure. The strength of the beams to resist horizontal shear was much affected by seasoning checks and ring shakes.

The following notes of the tests will assist in understanding the manner of failure of the beams. In reading, it will be well to refer to Plates 1 to 16 (frontispiece) and to the load-deflection diagrams at the end of the text.

A 1. Faint cracking at load of 15 000 lb. Loud cracking at 22 500 lb. After failure by horizontal shear at 26 000 lb. in a continuation of the test, the load increased, the stringer acting as two beams, failing by horizontal shear along a second crack at 38 000 lb. See Fig. 11.

A 2. Beyond 40 000 lb. cracking noises were heard. Sudden failure by horizontal shear at north end, resulting in the upper part of the beam projecting over the lower porton ¼ in. See Plates 1 and 9.

A 3. Failed suddenly with loud report, by horizontal shear at north end, at 67 500 lb. See Plate 9.

A 4. This beam proved to have a bad ring shake through the middle of the length of the beam, which was the occasion of the tension failure. See Plate 1.

TABLE 6.

Tests of Beams in Series C.

Stresses are given in lb. per. sq. in.

Des.	Cross Section in. x in.	Elastic Limit		Load at Failure			Manner of Failure
		Load pounds	Fiber Stress	Total pounds	Fiber Stress	Hor. Shearing Stress	
Shortleaf Pine.							
C 1	7.00 x 15.75	Not Reached		43 000	4016	293	Horizontal shear.
C 2	7.00 x 16.12	42 500	3780	45 000	4005	300	Horizontal shear.
C 3	7 00 x 16.38	50 000	4310	54 550	4715	358	Horizontal shear.
C 4	6.75 x 16.00	52 500	4940	72 500	6810	505	Horizontal shear.
C 5	7.00 x 16.00	35 000	3165	40 000	3620	268	Horizontal shear.
C 6	7.00 x 16.00	40 000	3620	47 500	4300	318	Horizontal shear.
C 7	7.25 x 16.12	27 500	2360	42 500	3655	273	Horizontal shear.
C 8	7.00 x 16.00	45 000	4065	47 970	4340	320	Horizontal shear.
C 9	7.00 x 16.00	30 000	2715	33 430	3025	224	Horizontal shear.
C 10	7.12 x 16.25	42 500	3660	55 000	4730	357	Tension
C 11	7.00 x 15 87	27 500	2530	37 000	3405	250	Tension
C 12	7.00 x 16·00	55 000	4970	61 370	5550	410	Horizontal shear.
Loblolly Pine.							
C 13	6.50 x 16.00	40 000	3900	53 000	5160	382	Horizontal shear.
C 14	6.87 x 16.00	42 500	3915	48 860	4500	334	Tension
C 15	7 00 x 16.25	45 000	3940	55 860	4890	368	Horizontal shear.
C 16	7.00 x 16.12	55 000	4900	58 400	5195	388	Horizontal shear.
C 17	7.00 x 16.00	30 000	2710	38 100	3445	255	Horizontal shear.
C 18	7.25 x 15.75	25 000	2155	37 300	3360	245	Horizontal shear.
C 19	7.12 x 16.00	30 000	2670	41 500	3695	273	Horizontal shear.
C 20	7.25 x 16.00	25 000	2180	34 550	3020	224	Horizontal shear.
C 21	7.62 x 15.75	22 500	1930	33 500	2870	209	Tension
C 22	7.50 x 16.50	27 500	2180	40 000	3175	243	Tension
C 23	7.38 x 16 50	25 000	2018	38 240	3085	236	Tension
C 24	7.25 x 16.12	32 500	2795	57 200	4915	368	Horizontal shear.

A 5. Upper portion projected ⅜ in. after failure by shear.

A 6. Selected to show effect of large knots. At 31 200 lb. loud cracking noise at middle. Failed at 31 700 lb. at large knot near middle. See Plate 1.

A 7. Failed by horizontal shear at north end. Large checks at south end seemed not to affect failure. See Plate 10.

A 8. Sudden failure by shear at 74 000 lb., the shear extending from the south end to the load point and the upper portion projecting ⅜ in. See Plate 10.

A 9. First failure at 39 750 lb., pure tension. Final failure at 46 850 lb., tension again. See Plate 2 and Fig. 11.

A 10. Knotty and cross-grained in middle third of length. Failed by tension near north load point, then splitting along neutral axis both ways from tension fracture. See Plate 2 and Fig. 11.

A 13. Slight splintering at bottom at 58 600 lb. Further breaking in tension at 60 000 lb. Final failure by horizontal shear at 63 300 lb.

TABLE 7.

DATA OF BEAMS IN SERIES A AND B.

Des.	Nominal Size in. x in. x ft.	Description	Condition
A 1	7 x 16 x 14	Longleaf pine (a)	Large seasoning checks.
A 2	7 x 16 x 14	Longleaf pine (a)	Large checks. Clear stick.
A 3	7 x 16 x 14	Longleaf pine (a)	Good stick.
A 4	7 x 16 x 14	Longleaf pine (a)	Proved to have bad shake.
A 5	7 x 16 x 14	Longleaf pine (a)	Even grain. Good condition.
A 6	7 x 16 x 14	Longleaf pine (a)	Large knots and cross grain.
A 7	7 x 16 x 14	Longleaf pine (a)	Clear and straight-grained.
A 8	7 x 16 x 14	Longleaf pine (a)	Stick clear.
A 9	7 x 14 x 14	Longleaf pine (a)	Bad checks and shakes.
A 10	7 x 14 x 14	Longleaf pine (a)	Cross-grained and knotty.
A 11	7 x 14 x 14	Longleaf pine (a)	Clear and free from knots.
A 12	7 x 14 x 14	Longleaf pine (a)	Clear, straight-grained.
A 13	7 x 14 x 14	Longleaf pine (a)	Fairly clear and straight-grained.
A 14	7 x 14 x 14	Longleaf pine (a)	Knotty and cross-grained.
A 15	7 x 12 x 14	Longleaf pine (b)	Large checks. Sapwood on bottom.
A 16	7 x 12 x 14	Longleaf pine (b)	Clear stick.
A 17	7 x 12 x 14	Longleaf pine (b)	Solid knots on top side.
A 18	7 x 12 x 14	Longleaf pine (b)	Small knots along neutral axis.
A 19	7 x 12 x 14	Longleaf pine (b)	Knot near middle.
A 20	7 x 12 x 14	Longleaf pine (b)	Checks near neutral axis.
B 1	7 x 16 x 14	Longleaf pine (c)	Fairly clear stick.
B 2	7 x 16 x 14	Longleaf pine (c)	Clear and straight.
B 3	7 x 16 x 14	Longleaf pine (c)	Clear stick.
B 4	7 x 16 x 14	Longleaf pine (c)	Grain straight. Clear.
B 5	7 x 16 x 14	Longleaf pine (c)	Grain straight. Clear.
B 6	7 x 16 x 14	Longleaf pine (c)	No knots. Cross-grained.
B 7	7 x 16 x 14	Longleaf pine (c)	Straight. No bad checks.
B 8	7 x 16 x 14	Longleaf pine (c)	Straight. No bad checks.
B 9	7 x 14 x 14	Longleaf pine (c)	Clear, straight grain. Large seasoning check.
B 10	7 x 14 x 14	Longleaf pine (c)	Grain straight. No knots.
B 11	7 x 14 x 14	Longleaf pine (c)	Straight, clear, free of checks.
B 12	7 x 14 x 14	Longleaf pine (c)	Straight, clear, free of checks.
B 13	7 x 14 x 14	Longleaf pine (c)	Straight, clear, free of checks.
B 14	7 x 14 x 14	Longleaf pine (c)	Cross-grained and knotty,

(a) Seasoned 18 months. (b) Seasoned 12 months. (c) Seasoned 4 months.

A 14. At 26 500 lb., failed at knot 2 ft. south of middle. See Plate 2.

A 15. At 22 500 lb. beam sheared at north end, along a wide open seasoning check, upper portion projecting $\frac{5}{16}$ in. Load fell to 20 000 lb. Under further test, projection reached $\frac{1}{2}$ in., and the beam finally failed at 30 000 lb. by tension under the north load. During this time the beam slipped quietly along seasoning check $2\frac{1}{2}$ in. below top on one face and 5 in. below top on the other. This shear gradually approached the middle of the span. After this slip commenced the stringer acted somewhat as two beams. See Fig. 12.

A 16. At 37 500 lb. slight splintering at bottom, and load fell to 34 000 lb., rising then to 39 400 lb. with further tension failure. The load fell to 36 000 lb. and with increased deflection rose to 40 900 lb., the final failure being in horizontal shear at the north end. See Plate 3 and Fig. 12.

A 17. This beam had a number of solid knots $\frac{3}{4}$ in. to $1\frac{3}{4}$ in. across, all at or near the upper surface. The tension side was clear. At 52 900 lb. the beam gave way by tension, the load then dropping slightly, and in about 5 seconds shear failure followed at south end, the upper portion sliding past the lower $\frac{5}{16}$ in. See Plate 11.

A 18. Bad ring checks at south end. Stick strengthened by small knots along neutral axis. See Plates 3 and 12.

TABLE 8.

Tests of Beams in Series A and B.

Stresses are given in lb. per sq. in.

Des.	Cross Section in. x in.	Elastic Limit		Load at Failure			Manner of Failure
		Load pounds	Fiber Stress	Total pounds	Fiber Stress	Hor. Shearing Stress	
A 1	6.75 x 15.37	19 500	1960	26 000	2640	188	Horizontal shear.
A 2	6.5 x 16.2	37 500	3060	47 500	4535	340	Horizontal shear.
A 3	7.0 x 16.25	62 500	5480	67 500	5910	445	Horizontal shear.
A 4	7.0 x 16.0	35 000	3150	40 000	3600	267	Tension.
A 5	7.0 x 16.0	53 500	4820	62 500	5640	418	Horizontal shear.
A 6	7.0 x 16.0	28 500	2570	31 700	2860	212	Tension.
A 7	7.0 x 16.0	43 000	3890	47 500	4300	318	Horizontal shear.
A 8	7.0 x 16.0	62 000	5630	74 000	6710	497	Horizontal shear.
A 9	7.0 x 14.0	34 500	4060	46 850	5520	359	Tension.
A 10	7.0 x 14.0	25 000	2940	25 000	2945	191	Tension.
A 11	7.0 x 14.0	48 500	5720	57 500	6820	441	Horizontal shear.
A 12	7.0 x 14.0	48 500	5700	59 050	6950	453	Horizontal shear.
A 13	7.0 x 14.12	47 500	5440	63 300	7260	472	Horizontal shear.
A 14	7.0 x 14.0	25 500	3010	37 300	4400	285	Tension.
A 15	6.87 x 12.0	22 500	3610	22 500	3690	205	Horizontal shear.
A 16	6.6 x 11.75	30 000	5830	39 400	7010	382	Tension.
A 17	7.0 x 12.1	36 500	5800	52 900	8410	471	Tension.*
A 18	6.5 x 11.94	30 000	5200	37 000	6410	356	Horizontal shear.
A 19	7.0 x 12.0	22 000	3540	31 650	5080	282	Tension.
A 20	6.87 x 12.0	32 500	5310	33 400	5460	304	Horizontal shear.
B 1	6.8 x 16.0	45 000	4180	52 500	4890	362	Horizontal shear.
B 2	7.0 x 16.0	56 000	5020	65 100	5880	436	Horizontal shear.
B 3	6.92 x 15.95	55 000	5080	68 000	6260	462	Horizontal shear.
B 4	7.20 x 16.32	61 600	5160	64 300	5430	410	Horizontal shear.
B 5	7.20 x 16.62	56 000	4560	75 600	6160	474	Horizontal shear.
B 6	6.87 x 16.06	56 000	5110	66 700	6080	454	Horizontal shear.
B 7	7.0 x 16.0	46 000	4150	58 350	5270	390	Horizontal shear.
B 8	6.9 x 15.95	40 000	3720	58 900	5430	401	Horizontal shear.
B 9	7.1 x 14.1	30 000	3440	31 600	3620	237	Horizontal shear.
B 10	7.12 x 14.06	41 000	4720	56 750	6540	425	Horizontal shear.
B 11	7.25 x 14.05	35 000	3960	36 900	4180	272	Horizontal shear.
B 12	7.05 x 14.0	41 500	4860	50 900	5970	387	Horizontal shear
B 13	6.87 x 14.0	33 000	3970	46 300	5570	362	Horizontal shear.
B 14	6.95 x 14.0	33 000	3560	44 600	5300	344	Tension.

* Followed quickly by horizontal shear.

A 19. Cracking sound at 22 000 lb., seemingly something giving way. Increased deflection above this load is shown on deflection diagram. Tension failure. Brash wood. See Plate 3.

A 20. Sheared suddenly at north end, plainly due to large seasoning checks. See Plate 12.

B 1. Considerable sapwood at top and bottom. Failed by horizontal shear along neutral axis. Shear in tortuous line. See Plate 13.

B 3. A load of 65 000 lb. was applied, giving a deflection of 1.36 in. After release of load a set of 0.06 in. was observed. At the second application of 65 000 lb. the deflection was 1.37 in. Failed by shear at north end at 68 000 lb.

B 9. Large, deep seasoning checks nearly continuous. Free from knots, failed in horizontal shear along seasoning check.

B 10. No seasoning checks except at extreme end. Failed by horizontal shear at high load.

TABLE 9.

DATA OF BEAMS IN SERIES D.

Des.	Nominal Size in. x in. x ft.	Description	Condition
D 1	7 x 16 x 14	Loblolly pine, untreated (a)	Large knot outside load point.
D 2	7 x 16 x 14	Loblolly pine, untreated (a)	Knot near middle.
D 3	7 x 16 x 14	Loblolly pine, untreated (a)	Several knots.
D 4	7 x 14 x 14	Loblolly pine, untreated (a)	Straight-grained and clear.
D 5	7 x 14 x 14	Loblolly pine, untreated (a)	Very knotty; no checks.
D 6	7 x 14 x 14	Loblolly pine, untreated (a)	Very knotty; no checks.
D 7	7 x 14 x 14	Loblolly pine, untreared (a)	Few knots.
D 8	7 x 14 x 14	Loblolly pine, untreated (a)	Slight cross-grain and checks.
D 9	7 x 14 x 14	Loblolly pine, untreated (a)	Straight-grained, 1 large check.
D 10	7 x 16 x 14	Loblolly pine, untreated (a)	Straight-grained, 1 large check.
D 11	7 x 16 x 14	Loblolly pine, untreated (a)	Knots on neutral axis.
D 12	7 x 16 x 14	Loblolly pine, untreated (a)	Straight-grained, fairly clear.
D 13	7 x 16 x 14	Loblolly pine, untreated (a)	Straight-grained.
D 14	7 x 16 x 14	Loblolly pine, untreated (a)	Cross-grained. A few knots and checks.
D 15	7 x 16 x 14	Loblolly pine, creosoted (b)	Large knots along neutral axis.
D 16	7 x 16 x 14	Loblolly pine, creosoted (b)	Large knots. Cross grain.
D 17	7 x 14 x 14	Loblolly pine, creosoted (b)	Cross grain.
D 18	7 x 14 x 14	Loblolly pine, creosoted (b)	Brash wood.
D 19	7 x 14 x 14	Loblolly pine, creosoted (b)	Good condition.
D 20	7 x 16 x 14	Loblolly pine, creosoted (b)	Knots along neutral axis.
D 21	7 x 14 x 14	Loblolly pine, creosoted (b)	Rather knotty at one end.
D 22	7 x 16 x 14	Loblolly pine, creosoted (b)	Straight-grained and clear.
D 23	7 x 16 x 14	Loblolly pine, creosoted (b)	Straight-grained and clear.
D 24	7 x 16 x 14	Loblolly pine, creosoted (b)	A few knots.
D 25	7 x 14 x 14	Loblolly pine, creosoted (b)	Several large knots.
D 26	7 x 14 x 14	Loblolly pine, creosoted (b)	Fairly clear and straight-grained.

(a) Seasoned 6 months. (b) Seasoned 2 months.

B 11. Seasoning checks, but not very marked or deep. Failed by horizontal shear along seasoning check.

B 13. 2 in. sapwood at top. Few seasoning checks. Free from knots. Bearing plate at north load induced crushing in upper fiber near it at a load 1000 lb. below maximum, and slight splintering tension failure occurred at bottom below this point, but main failure was by horizontal shear at the south end at the maximum load. The compression failure finally extended from the top fiber nearly to the neutral axis.

B 14. Failed by tension below a large knot which was on the compression side.

C 2. Failure by horizontal shear along seasoning crack 2 in. above neutral axis.

C 3. Failure by horizontal shear along neutral axis.

C 4. After failure by horizontal shear along neutral axis, upper portion projected ⅝ in. Highest shearing strength in this series.

C 5. Failed by horizontal shear under deflection of 1⅛ in. Load fell off. Upon increasing the deflection, it rose to 33 890 lb. and failed in tension under a deflection of 2 in.

C 7. Bearing plate under one load crushed unevenly into wood at 40 000 lb. Load released, plate adjusted, and load applied to failure.

C 8. Load of 35 000 lb. was released, bearing plate at support adjusted and load applied to failure (48 000 lb.). After failure by horizontal shear, load was further applied and failure in tension occurred at 39 600 lb. under a deflection 2½ in. more than at shear failure.

C 9. Failed by shearing at south end at 33 430 lb. under deflection of 1.09 in. Load dropped to 32 000 lb., then rose to 35 000 lb. under a deflection

TABLE 10.

Tests of Beams in Series D.

Stresses are given in lb. per sq. in.

Des.	Cross Section in. x in.	Elastic Limit		Load at Failure			Manner of Failure
		Load pounds	Fiber Stress	Total pounds	Fiber Stress	Hor. Shearing Stress	
D 1	6.87 x 16.0	41 500	3820	56 000	5150	381	Horizontal shear.
D 2	7.25 x 16.25	33 000	2790	48 700	4120	310	Tension.
D 3	7.13 x 16.8	27 000	2180	41 800	3360	262	Tension.
D 4	7.1 x 14.0	32 000	3730	49 100	5740	371	Horizontal shear.
D 5	7.2 x 14.0	17 000	1950	22 000	2530	164	Tension.
D 6	6.81 x 14.06	18 000	2160	29 300	3520	229	Tension.
D 7	7.05 x 13.72	30 000	3660	42 000	5130	325	Tension.
D 8	6.95 x 14.10	22 000	2620	29 350	3490	226	Tension.
D 9	6.55 x 14.05	27 000	3370	31 000	3880	253	Horizontal shear.
D 10	6.9 x 16.20	33 000	2950	42 000	3760	282	Horizontal shear.
D 11	7.25 x 16.0	32 500	2830	50 500	4410	326	Tension.
D 12	7.1 x 16.15	33 500	2940	46 800	4100	305	Horizontal shear.
D 13	7.25 x 16.45	37 500	3100	52 200	4310	328	Horizontal shear.
D 14	6.45 x 16.07	34 000	3320	38 700	3770	281	Horizontal shear.
D 15	7.1 x 16.25	42 500	3680	54 700	4740	356	Tension.
D 16	7.37 x 16.37	18 500	1460	32 500	2660	202	Tension.
D 17	7.0 x 14.0	30 000	3530	42 700	5030	327	Tension.
D 18	6.87 x 14.0	30 000	3600	41 700	5000	325	Tension.
D 19	7.0 x 14.0	34 000	4020	51 500	6080	394	Tension.
D 20	7.0 x 15.5	45 000	4330	46 400	4460	320	Horizontal shear.
D 21	7.75 x 14.0	40 000	4280	56 400	6020	391	Crush. and hor. shear.
D 22	7.1 x 16.5	42 500	3570	65 500	5500	420	Crushing and tension.
D 23	7.0 x 16.0	50 000	4510	56 500	5100	378	Crush. and hor. shear.
D 24	7.5 x 16.25	51 000	4180	55 475	4550	341	Crushing.
D 25	7.5 x 14.25	23 500	2500	31 100	3300	218	Tension.
D 26	7.0 x 13.75	27 500	3380	37 000	4540	289	Tension.

of 3.08 in., when the shearing fracture extended the entire length of the beam. Very low shearing strength.

C 10. Failed by tension at center due to cross grain. Contributory crushing under north support. Loading released. On second application, load reached 50 200 lb. under 3 in. additional deflection, when further failure in tension occurred.

C 11. Failure by tension due to knot under south load point.

C 13. Failed at one end by horizontal shear along neutral axis.

C 14. Failure by tension under south load point. Four knots near break.

C 15. Marked change in deflection curve evidently due to horizontal shearing action.

C 16. Slight splintering at bottom when horizontal shear failure occurred.

C 17. After horizontal shear failure at south end at 38 100 lb. load dropped, and on further deflection rose to 26 200 lb., the beam then failing by tension under south load point.

C 18. Crushing (bearing) under bearing plates at load points and over supports at the load which gave horizontal shear failure.

C 19. Crushing (bearing) over bearing plate at north support showed at 27 500 lb. At 40 000 lb. crushing was so great that load was released and support adjusted. Failure by horizontal shear at 41 500 lb.

TABLE 11.

Data of Beams in Series E and F.

Des.	Nominal Size in. x in. x ft.	Description	Condition
E 1	7 x 16 x 15	Old Douglas fir (a)	Straight-grained.
E 2	7 x 16 x 15	Old Douglas fir (a)	Straight-grained.
E 3	7 x 16 x 15	Old Douglas fir (a)	Straight-grained.
E 4	7 x 16 x 15	Old Douglas fir (a)	
E 5	7 x 16 x 15	Old Douglas fir (a)	Straight-grained.
E 6	7 x 16 x 15	Old Douglas fir (a)	Small unimportant knots.
E 7	7 x 16 x 15	Old Douglas fir (a)	Straight-grained. Few knots.
E 8	7 x 16 x 15	Old Douglas fir (a)	Knotty and cross-grained.
E 9	7 x 16 x 15	Old Douglas fir (a)	Knotty and rather crooked grain.
E 10	7 x 16 x 15	Old Douglas fir (a)	Crooked grain, one large knot.
E 11	7 x 16 x 15	Old Douglas fir (a)	Fairly straight-grained.
E 12	7 x 16 x 15	Old Douglas fir (a)	Numerous knots. Crooked grain.
F 1	8 x 16 x 15	New Douglas fir (b)	Fairly clear stick.
F 2	8 x 16 x 15	New Douglas fir (b)	Several large solid knots.
F 3	8 x 16 x 15	New Douglas fir (b)	Large seasoning checks.
F 4	8 x 16 x 15	New Douglas fir (b)	Large seasoning checks.
F 5	8 x 16 x 15	New Douglas fir (b)	Prominent seasoning checks.
F 6	8 x 16 x 15	New Douglas fir (b)	Deep seasoning checks.
F 7	8 x 16 x 15	New Douglas fir (b)	Very knotty. Cross-grained.
F 8	8 x 11 x 15	New Douglas fir (b)	Very knotty. Cross-grained.
F 9	8 x 16 x 15	New Douglas fir (b)	Straight-grained. Large checks.
F 10	8 x 16 x 15	New Douglas fir (b)	Cross-grained. Prominent check.
F 11	8 x 16 x 15	New Douglas fir (b)	Slightly cross grained. A few small knots.
F 12	8 x 16 x 15	New Douglas fir (b)	Fairly straight-grained. Small knots.
F 13	8 x 16 x 15	New Douglas fir (b)	Fairly straight-grained. Small knots.
F 14	8 x 16 x 15	New Douglas fir (b)	Straight-grained.
F 15	8 x 16 x 15	New Douglas fir (b)	Knotty and cross-grained.
F 16	8 x 16 x 15	New Douglas fir (b)	Numerous small knots.

(a) Seasoned 11 years. (b) Partly seasoned.

C 20. At 26 600 lb. tension break in lower fiber near knot occurred. Effect of this is shown in deflection curve. Failure by horizontal shear at 34 550 lb. See Fig. 15.

C 21. Failure by tension at knot under north load. Contributory crushing under bearing plate at same load.

C 22. Failure by tension under south load near knot.

C 23. Failure by tension. Cross-grained.

C 24. Failure by horizontal shear, with splintering at bottom.

D 1. Large amount of sapwood, 3 in. at bottom. Three rings to 1 inch. Marked seasoning checks at ends and sides. Large deflection. Failure by horizontal shear. Shearing fracture influenced by crooked grain around knot. See Plate 4.

D 2. Four inches of sapwood at top, 3 in. at bottom. Free from seasoning checks except at ends. Large knot near middle at bottom. Loud cracking noise at 47 000 lb. Failed by tension at knot near middle, followed at once by horizontal shear. See Plates 4 and 14.

D 3. Large amount of sapwood, 4 in. at top and at bottom. Coarse wood. Large knot near top on east side near middle of length. Beam tilted on loading. Load released, beam straightened up and load applied. Failed in tension by splintering along the bottom. See Plate 14.

D 4. Large amount of sapwood, 4 in. at top and 3 in. at bottom. Straight-grained. Fairly free from seasoning cracks and knots. Failed by shear with tension break at same time under south load. See Plate 14.

D 5. Heart at west face. Wood coarse and brash. East face sapwood, quite soft. Large knot (5 in.) under upper bearing plate and large knot

TABLE 12.

TESTS OF BEAMS IN SERIES E AND F.

Stresses are given in lb. per sq. in.

Des.	Cross Section in. x in.	Elastic Limit		Load at Failure			Manner of Failure
		Load pounds	Fiber Stress	Total pounds	Fiber Stress	Hor. Shearing Stress	
E 1	6.6 x 15.45	27 500	3050	30 000	3320	221	Horizontal shear.
E 2	6.7 x 15.55	50 000	5360	51 400	5510	369	Horizontal shear.
E 3	6.81 x 15.31	45 000	4970	47 700	5270	378	Horizontal shear.
E 4	7.0 x 15.75	32 500	3260	37 500	3770	256	Horizontal shear.
E 5	6.75 x 15.63	30 000	3160	32 500	3430	231	Horizontal shear.
E 6	6.75 x 15.5	32 500	3490	33 600	3610	241	Horizontal shear.
E 7	6.63 x 15.88	28 500	2960	37 500	3910	268	Horizontal shear.
E 8	7.0 x 15.88	42 000	4120	42 000	4120	282	Tension
E 9	6.75 x 15.5	47 500	5090	53 500	5730	383	Horizontal shear.
E 10	6.75 x 15.88	22 500	2260	32 500	3260	223	Tension.
E 11	6.75 x 15.75	45 000	4660	47 800	4980	337	Horizontal shear.
E 12	7.0 x 16.0	35 000	3500	45 000	4500	301	Horizontal shear.
F 1	8.0 x 15.85	43 000	3730	49 100	4260	291	Horizontal shear.
F 2	8.0 x 15.95	40 000	3420	46 600	3990	275	Horizontal shear.
F 3	8.0 x 15.87	45 500	3940	48 850	4220	289	Horizontal shear.
F 4	7.9 x 15.80	39 500	3410	47 000	4150	282	Horizontal shear.
F 5	8.0 x 15.77	57 000	4980	58 000	5070	345	Horizontal shear.
F 6	7.9 x 15.90	56 000	4890	57 000	4970	340	Horizontal shear.
F 7	7.7 x 15.55	33 500	2920	38 200	3690	239	Tension.
F 8	7.7 x 15.60	27 500	2550	35 000	3250	219	Tension.
F 9	8.0 x 15.75	52 500	4700	67 500	6040	401	Horizontal shear.
F 10	8.0 x 16.0	37 500	3180	42 500	3610	332	Tension.
F 11	8.0 x 15.63	46 500	4080	51 250	4510	304	Horizontal shear.
F 12	8.0 x 16.0	50 000	4250	62 500	5310	366	Horizontal shear.
F 13	8.0 x 16.13	48 500	4020	52 500	4340	302	Horizontal shear.
F 14	8.0 x 15.88	50 000	4280	57 500	4710	322	Tension.
F 15	8.0 x 16.13	52 500	4370	65 000	5400	376	Horizontal shear.
F 16	8.13 x 15.88	54 000	4560	61 350	5180	355	Tension.

(4 in.) near bottom and under north load. Not merchantable stick. Failure by tension under north load.

D 6. Three inches of sapwood at top and bottom. Large knots near neutral axis. Failed by tension near large knot. Coarse dark-colored sapwood at point of failure. Little bond between rings. Ring shake developed in middle third.

D 7. Little sapwood. Straight-grained. The prominent seasoning cracks were staggered towards the ends and seemed not to affect the strength. Failed in tension at standard knot in middle of bottom face.

D 8. Very coarse wood, free from seasoning checks, knots under each load point. Failed by tension, the fracture running from the bottom under one load point to the top under the other.

D 9. Good grain for loblolly. Very marked seasoning checks on both faces through north third of length. Failed by horizontal shear at north end along these prominent seasoning checks.

D 10. Straight grained. Coarse wood. Little sapwood. Large knot at neutral axis at south end. Failed by horizontal shear at north end along deep seasoning check.

D 11. Many knots along neutral axis. Large amount of sapwood, 4 in. at bottom and 2 in. at top. Marked seasoning checks on west face, but staggered. Numerous knots along neutral axis. Failed by tension; probably due to sapwood. See Plate 4.

D 12. Free from seasoning checks. Knots not at important places. Failed in tension under south load. Fair break. Timber seemed soft and brash.

D 13. Free from seasoning checks. Brashy sapwood on under side. Several small spike knots. Failure by tension in sapwood.

D 14. Failed at south end by shear along seasoning checks, which were near neutral axis on west side but on east side ran toward bottom at south end.

D 15. Failed by tension at center. Load fell off to 42 000 lb., when crushing began above the tension failure.

D 16. Five knots on east side 1½ to 3 in. On west side one knot 2 x 9 in. and one 1½ x 8 in., both extending to bottom of beam. Not merchantable stick. Abnormally large deflection. Failure by tension near large knot.

D 17. Three large knots. Failed by tension at knot under south load.

D 18. The wood seemed brittle and of inferior quality. Splintering at bottom at load of 37 500 lb. Failure was sudden and complete, the stick being badly shattered and not capable of carrying any load. See Plate 5.

D 19. At 46 500 lb. slight splintering at bottom. At 51 500 lb. popping noise at middle. Load gradually dropped to 49 100 lb. Then beam gave way, there being three distinct loud pops about ½ second apart as the beam failed by tension at the middle.

D 20. Slight splintering on under side near maximum load. Final failure by shear near north end. When failure occurred, the north support was thrown out to the north against a pile of beams, the beam itself shot out south 5 ft. Creosote had been squeezed out of the wood over the bearing plates, and slipping thus more easily occurred.

D 21. Several large knots in north half, which apparently did not affect the strength at the load reached. Crushing began under north load at 56 000 lb., the load went up to 56 400 lb., then dropped to 56 200 lb., when failure by crushing and horizontal shear occurred simultaneously. See Plates 5 and 14.

D 22. At 59 750 lb. slight splintering on bottom. At 63 500 lb. piece splintered off below north load to north end. Bearing plate crushing into wood. At 64 500 lb. crushing apparent north of north load. Largest load 65 500 lb., when stick reached bed of machine, still carrying the load. Failure combination of tension and compression. See Fig. 17.

D 23. At 51 650 lb. crushing became apparent at north load and deflections beyond this were much increased. Failure at 56 500 lb. by crushing and horizontal shear at north end simultaneously.

D 24. This beam is a good illustration of the action of several of the creosoted loblolly stringers. Beyond 52 500 lb. the deflection increased very rapidly, and the stick seemed to act like water-soaked or steamed wood, bending like a very soft wood. Although slight splintering occurred on the bottom at the north end, failure was due to crushing which was quite apparent at both load points at 52 700 lb. (evidently occasioned by the bearing blocks crushing into the wood), and failure occurred at 56 300 lb.

D 25. Failed by tension at knot near south load. Beam lacked stiffness. See Plate 5.

D 26. Tension failure under north load.

E 1. At 29 800 lb. loud cracking occurred and load fell off to 20 000 lb.—evidently a shear failure. Load picked up and deflections increased rapidly thereafter, the stick acting as two beams. At 40 000 lb. the upper portion of south end was projecting ½ in. The maximum load carried was 43 800 lb. See Plates 6 and 15 and Fig. 18.

E 2. Failure along seasoning crack by horizontal shear at 51 400 lb. with loud report. Load dropped to 24 000 lb.; stiff beam.

E 3. The great increase in deflection after load of 44 800 lb. was evidently due to incipient shear failure and not to fiber elastic limit having been reached. Sheared at south end (sawed end) at 47 700 lb. along a line 4 in. below top. Load dropped to 30 400 lb. rose to 40 000 lb. after a further deflection of 0.62 in., when it failed by horizontal shear at the same end along a second line 3 in. from bottom.

E 4. Failed by horizontal shear at north end. This end was the sawed end and was originally next to the end which failed in E 3.

E 5. Failed by horizontal shear at sawed end 7 in. below top at 32 500 lb. Load dropped to 15 750 lb. Load rose to 34 300 lb. when the beam sheared again at same end, this time 4 in. above bottom. The load then dropped to 22 700 lb. See Plate 15.

E 6. Failure by horizontal shear at sawed end 7 in. below top at 33 600 lb. Load dropped to 20 000 lb. and finally rose to 29 100 lb. when it sheared again at the same end, this time 5 in. above bottom. Load dropped to 14 000 lb.

E 7. Failed by horizontal shear at unsawed end at mid-depth at 37 500 lb. Load dropped to 22 500 lb. With the deflection increased from 0.8 in. to over 3 in., the load rose to a maximum of 47 300 lb., when splintering at the bottom occurred. See Plate 15.

E 8. Failed by splintering tension at 42 000 lb. Strength affected by cross-grain.

E 9. Failed at sawed end by horizontal shear along inclined line at 53 500 lb. Load dropped to 28 000 lb. and with 1.5 in. additional deflection rose to 41 300 lb. The view shows final break. See Plate 6.

E 10. Large knot at center of bottom. At 23 100 lb. splitting began on tension side, and deflection increased rapidly after this. Failed by tension at 32 500. lb. See Plate 6 and Fig. 18.

E 11. Failed by horizontal shear at sawed end at 47 800 lb. Load fell to 27 600 lb. With increased deflection load rose to 49 900 lb., when the beam failed by tension at the middle. See Plate 15.

E 12. At 36 700 lb., 37 900 lb., and 38 200 lb., there were slight splinterings, accompanied each time by slight drop in load. Failed at unsawed end by horizontal shear at 45 000 lb. Load fell to 26 950 lb.

F 1. Failed at sawed end by horizontal shear at 49 100 lb. Failure cracks inclined. Tension splintering also occurred under north load. See Plate 16.

F 2. Very knotty stick. Large knot at bottom under north load. Another knot one foot away. At 44 700 lb. seemingly giving way in tension at middle, with loud report. Increased deflection afterward. Failure by horizontal shear along neutral axis at 46 600 lb. although at 44 700 lb. a loud report and seeming failure at bottom indicated an approaching tension failure. See Plate 7.

F 3. Failure by horizontal shear at 48 850 lb. Load dropped to 25 000 lb. See Plate 7.

F 4. Failure at unsawed end by horizontal shear at 47 000 lb. Loud report. See Plate 7.

F 5. Failure at unsawed end by horizontal shear along prominent seasoning cracks opposite heart at 58 000 lb. Line of shear across middle 4 in. followed around annual ring.

F 6. Somewhat cross-grained. Several large knots near neutral axis. One 2-in. knot in middle near top. Deep seasoning checks opposite heart. Failed at unsawed end by horizontal shear at 57 000 lb. See Plate 16.

F 7. Tension failure. The grain around a knot just below the middle was quite irregular. A shake also showed itself along the fracture. See Plate 8.

F 8. Considerable sapwood. Cracking noise at 27 500 lb. Loud cracking at 32 500 lb. Tension failure under south load point, followed immediately by horizontal shear at the north (sawed) end.

F 9. Heart at one face. Loaded twice—first time to 61 300 lb. Deflection set on release of load, 0.13 in. At second application of this load deflection was 0.25 in. greater than on first loading. Failed at unsawed end by horizontal shear at 67 500 lb.

F 10. Heart at one face. Cross-grained. Cracking noises at each application of load from 20 000 lb. on. Tension failure at 42 500 lb. Cross-grained failure. See Plate 8.

F 11. Cracking noises in middle at several loads from 12 500 lb. on. Failed at sawed end by horizontal shear at 51 250 lb. See Plate 16.

F 12. Failed at unsawed end by horizontal shear.

F 13. Failed at unsawed end by horizontal shear through heart.

F 14. Failed by tension under south load point, followed immediately by horizontal shear at the unsawed end. See Plates 8 and 16.

F 15. Failed at unsawed end by horizontal shear, followed by slight tension failure on west side in middle third.

F 16. Cracking noises on application of loads from 17 500 lb. on. Failure by tension, the splinter starting from large knot under south load point.

15. *Shear Test Data.*—In Table 13, are given data of the shearing tests of blocks cut from the full-size stringers of Series A, B, D, E, and F. In pieces from creosoted sticks the failure was gradual, something like a yield point being noticed, and there was a considerable longitudinal movement before final failure. In the untreated pieces the failures were generally quite sudden. In the few pieces in which small knots were present along the line of the shearing surface, greater resistance to shear was noted. Generally speaking, failure was more frequently along seasoning checks or else the failure line coincided with such checks for some distance. Plates 17 and 18 give views of shear test pieces after test and also show the position of seasoning checks.

16. *Small Beam Test Data.*—In Table 13 data of the cross-bending tests of small beam test pieces taken from stringers in Series A, B, D, E, and F are given. The failures were generally by tension or compression and at loads well above the elastic limit of the material.

17. *General Results of Tests.*—Table 14 gives a summary of the results of the tests of stringers and of the minor test pieces taken from them. Care should be exercised to take into consideration the differences in conditions before drawing conclusions, as, for example, the obvious defects of some of the sticks, the

TABLE 13.

TESTS OF MINOR TEST PIECES.

Stresses are given in lb. per sq. in.

Small Beams, 3 x 3 x 40 inches					Shear Blocks Approximately 7 x 12 in.	
Des.	Elastic Limit	Fiber Stress	Hor. Shear'g Stress	Manner of Failure	Designation	Shearing Stress
A 1a	10 640	12 000	750	Tension	A 1y	644
A 1b	8 780	10 450	654	Tension	A 1z	497
A 1c	6 675	10 000	625	Tension		
A 1d	6 680	10 000	625	Tension		
A 2a	9 525	13 800	860	Tension	A 2y	324
A 2b	8 700	8 700	533	Tension	A 2z	292
A 2c	6 670	10 000	625	Tension		
A 2d	6 675	10 000	625	Tension		
A 3a	6 950	9 980	622	Tension	A 3y	785
A 3b	7 990	10 350	647	Tension	A 3z	454
A 3c	6 470	6 470	396	Tension		
A 3d	5 430	8 760	475	Tension		
A 4a	8 270	10 050	629	Tension	A 4y	629
A 4b	8 000	8 670	541	Tension	A 4z	359
A 4c	4 170	4 580	292	Tension		
A 4d	4 260	4 650	292	Tension		
A 5a	5 330	9 730	608	Tension	A 5y	521
A 5b	6 810	10 900	682	Tension	A 5z	336
A 5c	5 360	5 360	333	Tension		
A 5d	6 650	7 520	472	Tension		
A 6a	5 850	6 860	430	Tension	A 6y	609
A 6b	10 000	10 950	683	Tension	A 6z	680
A 6c	6 000	8 400	524	Tension		
A 6d	6 660	8 060	504	Tension		
A 7a	8 520	10 850	680	Tension		
A 7b	6 940	10 600	664	Tension		
A 7c	8 000	10 000	625	Tension		
A 7d	6 270	8 800	550	Tension		
A 8a	6 670	8 800	550	Tension	A 8y	710
A 8b	4 270	4 400	275	Tension	A 8z	482
A 8c	6 200	6 200	388	Tension		
A 8d	7 480	8 720	583	Tension		
A 9a	2 130	3 510	219	Hor. shear	A 9y	428
A 9b	6 390	7 560	463	Tension	A 9z	514
A 9c	5 600	10 000	625	Hor. shear		
A 9d	5 875	7 840	491	Tension		
A 10a	6 800	9 740	608	Tension	A10y	134
A 10b	4 000	4 000	250	Tension	A10z	35
A 10c	6 800	8 540	533	Tension		
A 10d	6 670	8 860	545	Tension		
A 11a	6 670	8 200	513	Tension	A11y	357
A 11b	6 820	10 900	613	Tension	A11z	398
A 11c	6 280	9 810	680	Tension		
A 11d	7 170	10 300	647	Tension		
A 12a	8 000	10 000	625	Tension	A12y	444
A 12b	5 330	5 330	333	Hor. shear	A12z	384
A 12c	5 570	8 600	540	Tension		
A 12d	8 140	9 300	582	Tension		

TABLE 13. (*Continued*)

Tests of Minor Test Pieces.

Stresses are given in lb. per sq. in.

Small Beams, 3 x 3 x 40 inches					Shear Blocks Approximately 7 x 12 in.	
Des.	Elastic Limit	Fiber Stress	Hor. Shear'g Stress	Manner of Failure	Designation	Shearing Stress
A 13a	6 140	8 940	558	Tension	A13y	530
A 13b	6 675	9 940	621	Tension	A13z	783
A 13c	7 210	10 400	650	Tension		
A 13d	10 000	11 650	728	Tension		
A 14a	7 650	11 750	720	Tension	A14y	316
A 14b	5 980	7 050	442	Tension	A14z	410
A 14c	4 800	5 330	333	Hor. shear		
A 14d	6 000	8 720	547	Hor. shear		
A 15a	8 000	8 320	522	Hor. shear		
A 15b	10 150	13 500	842	Tension		
A 15c	6 675	10 650	668	Tension		
A 15d	9 340	9 340	583	Tension		
A 16a	6 680	10 050	630	Tension	A16y	506
A 16b	6 660	10 650	667	Tension	A16z	594
A 16c	4 000	5 730	358	Tension		
A 16d	7 330	9 100	569	Tension		
A 17a	7 930	11 500	719	Tension		
A 17b	8 500	10 100	619	Tension		
A 17c	8 670	9 860	617	Tension		
A 17d	8 660	10 400	650	Hor. shear		
A 18a	7 890	7 890	503	Hor. shear	A18y	588
A 18b	7 450	9 050	567	Hor. shear	A18z	525
A 18c	5 320	9 450	592	Tension		
A 18d	6 680	10 050	629	Tension		
A 19a	4 670	6 000	375	Tension	A19y	456
A 19b	5 450	6 370	397	Tension	A19z	392
A 19c	2 670	3 270	204	Tension		
A 19d	4 410	4 670	292	Tension		
A 20a	8 000	10 000	625	Crushing	A20y	280
A 20b	8 000	10 150	635	Tension		
A 20c	8 650	8 650	542	Tension		
A 20d	9 350	9 350	583	Tension		
Av.	6 835	8 810	550			466
B 1b	5 380	7 000	432	Crushing	B 1y	488
B 1c	5 140	7 320	474	Crushing	B 1z	546
B 2a	7 850	8 900	561	Tension	B 2y	353
B 2b	7 380	9 850	612	Crushing	B 2z	515
B 2c	5 940	6 980	436	Crushing		
B 2d	5 300	7 550	472	Crushing		
B 3a	6 340	8 180	513	Crushing	B 3y	272
B 3b	5 860	6 900	434	Crushing	B 3z	585
B 3c	5 950	8 600	541	Tension		
B 3d	6 460	9 000	560	Tension		
B 4a	7 725	11 300	702	Crushing	B 4y	221
B 4b	7 330	10 900	668	Crushing	B 4z	423
B 4c	6 550	10 900	670	Tension		
B 5a	9 880	12 300	733	Crushing	B 5y	378
B 5b	9 060	11 800	716	Crushing	B 5z	524
B 5c	7 200	9 100	322	Tension		
B 5d	7 180	9 600	560	Crushing		

TABLE 13. (*Continued*)

TESTS OF MINOR TEST PIECES

Stresses are given in lb. per sq. in.

Small Beams, 3 x 3 x 40 inches					Shear Blocks Approximately 7 x 12 in.	
Des.	Elastic Limit	Fiber Stress	Hor. Shear'g Stress	Manner of Failure	Designation	Shearing Stress
B 6a	4 920	6 620	416	Crushing	B 6y	366
B 6b	5 430	7 640	473	Crushing	B 6z	505
B 6c	6 720	8 850	552	Tension		
B 6d	7 000	9 440	591	Crushing		
B 7a	5 650	7 630	476	Crushing	B 7y	362
B 7b	5 430	7 130	445	Crushing	B 7z	376
B 7c	5 220	7 400	460	Crushing		
B 7d	4 750	7 060	437	Tension		
B 8a	5 300	6 100	380	Crushing	B 8y	386
B 8b	5 520	6 500	408	Crushing	B 8z	465
B 8c	6 440	8 220	508	Tension		
B 8d	6 240	9 340	583	Tension		
B 9a	7 250	9 450	578	Crushing	B 9y	254
B 9b	6 540	7 410	619	Crushing	B 9z	375
B 9c	5 960	9 700	600	Tension		
B 9d	6 490	10 000	618	Tension		
B 10a	6 475	8 250	508	Crushing	B10y	276
B 10b	5 590	7 450	468	Crushing	B10z	341
B 10c	6 150	9 850	609	Tension		
B 10d	5 960	9 000	563	Tension		
B 11a	5 010	6 850	430	Crushing	B11y	381
B 11b	5 150	6 800	427	Crushing	B11z	392
B 11c	5 670	8 800	549	Tension		
B 11d	5 460	8 530	532	Tension		
B 12a	6 190	8 740	543	Crushing	B12y	324
B 12b	5 910	7 750	483	Tension	B12z	454
B 12c	4 325	5 500	345	Tension		
B 12d	5 550	5 550	350	Tension		
B 13a	5 580	7 050	438	Crushing	B13y	177
B 13b	6 125	7 650	478	Crushing	B13z	519
B 13c	4 940	8 000	497	Tension		
B 13d	5 650	9 200	578	Tension		
B 14a	5 220	6 250	397	Tension	B14y	393
B 14b	5 250	6 550	413	Tension	B14z	362
Av,	6 110	8 280	513			393
D 1a	6 310	7 900	474	Crushing	D 1y	161
D 1b	5 920	8 000	491	Tension	D 1z	294
D 1c	5 180	6 450	389	Crushing		
D 1d	4 540	6 450	381	Tension		
D 2a	3 690	5 000	313	Crushing	D 2y	563
D 2b	5 740	7 000	424	Tension	D 2z	523
D 2c	2 990	3 800	234	Hor. Shear		
D 2d	4 410	5 600	347	Crushing		
D 3b	4 790	5 700	358	Tension	D 3y	451
D 3c	3 400	3 400	214	Tension	D 3z	400
D 3d	3 610	4 000	252	Tension		

TABLE 13. (*Continued*)

TESTS OF MINOR TEST PIECES.

Stresses are given in lb. per sq. in.

Small Beams, 3 x 3 x 40 inches					Shear Blocks Approximately 7 x 12 in.	
Des.	Elastic Limit	Fiber Stress	Hor. Shear'g Stress	Manner of Failure	Desig- nation	Shearing Stress
D 4a	6 340	8 450	528	Crushing	D 4y	493
D 4b	5 500	8 300	520	Crushing	D 4z	600
D 4c	5 420	7 400	460	Crushing		
D 4d	4 910	6 100	382	Crushing		
D 6a	3 490	4 500	279	Tension	D 6y	327
D 6b	3 710	4 800	276	Tension	D 6z	359
D 6c	3 050	4 450	278	Tension		
D 6d	3 090	4 700	292	Crushing		
D 7b	5 900	8 300	512	Tension	D 7y	407
D 7c	5 620	7 400	468	Tension	D 7z	115
D 7d	5 370	7 200	451	Crushing		
D 8a	4 425	5 500	342	Tension	D 8y	286
D 8b	3 700	5 300	332	Tension	D 8z	390
D 8c	2 890	4 200	264	Crushing		
D 8d	3 010	4 700	297	Tension		
D 9a	4 330	6 500	406	Tension	D 9y	320
D 9b	5 180	6 000	369	Tension	D 9z	445
D 9c	4 510	6 100	383	Crushing		
D 9d	4 110	6 100	378	Tension		
D 10a	6 030	7 500	466	Crushing	D10y	481
D 10b	4 570	6 800	435	Crushing	D10z	348
D 10c	4 270	6 000	374	Crushing		
D 10d	4 200	5 900	367	Crushing		
D 11a	4 280	7 000	438	Tension	D11y	742
D 11b	4 580	6 100	387	Tension	D11z	557
D 11c	3 490	4 900	308	Crushing		
D 11d	3 540	5 100	318	Crushing		
D 12a	4 610	5 650	355	Crushing	D12y	430
D 12b	4 210	6 300	402	Crushing	D12z	513
D 12c	3 550	5 400	338	Tension		
D 12d	3 560	5 200	333	Tension		
D 13a	4 020	6 700	417	Tension	D13y	549
D 13b	5 310	6 700	407	Tension	D13z	415
D 13c	4 780	6 200	378	Crushing		
D 13d	4 500	6 600	397	Crushing		
D 14a	5 000	6 050	377	Hor. shear	D14y	143
D 14b	3 400	3 400	212	Hor. shear	D14z	176
D 14c	5 610	7 400	468	Tension		
D 14d	5 600	7 600	484	Crushing		
Av.	4 485	6 035	375			403
D 16a	1 470	1 880	114	Tension	D16y	406
D 16d	816	816	51	Tension	D16z	551
D 17a	4 000	4 670	292	Tension	D17y	412
					D17z	440
D 18a	4 850	4 850	304	Tension	D18y	227
D 18c	4 750	6 000	375	Tension	D18z	141

TABLE 13. (*Continued*)

TESTS OF MINOR TEST PIECES.

Stresses are given in lb. per sq. in.

Small Beams, 3 x 3 x 40 inches.					Shear Blocks Approximately 7 x 12 in.	
Des.	Elastic Limit	Fiber Stress	Hor. Shear'g Stress	Manner of Failure	Designation	Shearing Stress
D 19a	7 060	9 000	552	Hor. shear	D19y	502
D 19b	6 010	6 060	380	Tension	D19z	254
D 19c	3 760	4 920	302	Hor. shear		
D 19d	3 600	4 340	271	Hor. shear		
D 20a	4 050	5 360	336	Tension	D20y	590
D 20b	4 310	6 400	402	Tension	D20z	556
D 20c	4 240	6 550	410	Tension		
D 20d	4 450	6 850	418	Crushing		
D 21a	5 730	7 540	472	Tension	D21y	647
D 21b	6 380	8 510	522	Tension	D21z	542
D 21c	4 180	4 570	298	Hor. Shear		
D 21d	5 020	5 060	309	Hor. Shear		
D 22a	7 450	8 400	526	Tension	D22y	450
D 22b	6 400	8 000	500	Hor. shear	D22z	479
D 22c	5 340	6 670	417	Tension		
D 22d	6 250	7 600	465	Tension		
D 23a	7 770	9 010	553	Crushing	D23y	163
D 23b	6 790	8 490	520	Tension	D23z	401
D 23c	5 675	7 750	474	Tension		
D 23d	5 090	7 230	443	Crushing		
D 24a	5 680	5 890	362	Tension	D24y	572
D 24b	5 090	7 120	438	Tension	D24z	483
D 24c	4 120	5 780	355	Tension		
D 24d	4 720	6 140	376	Tension		
D 25a	5 310	6 550	395	Tension	D25y	418
D 25b	4 150	5 190	319	Tension	D25z	448
D 25c	2 780	4 170	256	Tension		
D 25d	4 000	4 600	282	Tension		
D 26a	4 730	6 770	378	Tension	D26y	515
D 26b	6 100	7 270	445	Tension	D26z	498
D 26c	3 730	5 120	320	Tension		
D 26d	7 050	8 490	530	Tension		
Av.	4 945	6 210	383			441
E 1a	8 200	10 300	647	Hor. shear	E 1y	98
E 1b	4 560	8 950	565	Tension	E 1z	250
E 1c	8 270	10 300	647	Tension		
E 1d	8 700	11 200	704	Tension		
E 2a	7 290	9 800	613	Tension		
E 2b	9 150	12 100	758	Tension		
E 2c	6 975	7 900	495	Tension		
E 2d	9 300	9 300	582	Tension		
E 3a	8 950	9 350	583	Tension	E 3y	664
E 3b	9 300	10 250	641	Tension	E 3z	514
E 3c	5 330	7 200	348	Tension		
E 3d	4 080	7 650	478	Hor. shear		
E 4a	6 800	8 840	541	Tension	E 4y	535
E 4b	8 000	10 000	625	Hor. shear	E 4z	492
E 4c	7 270	10 170	683	Tension		
E 4d	7 680	10 170	650	Tension		

TABLE 13. (*Continued*)

TESTS OF MINOR TEST PIECES.

Stresses are given in lb. per sq. in.

Small Beams, 3 x 3 x 40 inches.					Shear Blocks Approximately 7 x 12 in.	
Des.	Elastic Limit	Fiber Stress	Hor. Shear'g Stress	Manner of Failure	Designation	Shearing Stress
E 5a	8 610	8 640	530	Tension	E 5y	792
E 5b	4 870	6 480	533	Tension	E 5z	529
E 5c	10 770	10 770	670	Crushing		
E 5d	8 160	11 480	718	Crushing		
E 6a	7 330	11 010	574	Tension	E 6y	354
E 6c	7 230	9 860	535	Tension	E 6z	318
E 6d	6 800	8 120	508	Tension		
E 7a	10 550	14 410	812	Crushing	E 7y	336
E 7b	6 950	8 820	539	Tension	E 7z	450
E 7c	7 220	10 200	625	Tension		
E 7d	6 860	9 380	583	Tension		
E 8a	8 780	12 820	802	Crushing	E 8y	293
E 8b	3 010	4 740	296	Tension	E 8z	375
E 8c	6 250	9 440	590	Hor. shear		
E 8d	7 450	9 450	592	Tension		
E 9a	5 470	7 270	454	Tension	E 9y	659
E 9b	6 790	9 460	592	Hor. shear	E 9z	511
E 9c	7 180	9 180	572	Tension		
E 9d	9 460	10 950	685	Tension		
E10a	8 240	10 020	626	Tension	E10y	635
E10b	4 960	5 300	331	Hor. shear	E10z	544
E10c	7 710	8 340	531	Tension		
E10d	8 430	11 780	743	Tension		
E11a	6 570	7 660	451	Hor. shear	E11y	611
E11b	7 970	9 680	607	Tension	E11z	695
E11c	2 230	3 130	189	Hor. shear		
E11d	6 670	8 860	541	Tension		
E12a	5 420	6 970	438	Tension	E12y	597
E12b	7 650	10 030	642	Tension	E12z	437
E12c	3 640	5 630	354	Tension		
E12d	6 650	8 920	558	Tension		
Av.	7 145	9 200	570			486
F 1a	4 489	4 600	294	Tension	F 1y	186
F 1b	6 780	7 200	448	Tension	F 1z	394
F 1c	3 740	5 150	323	Tension		
F 2a	6 375	7 650	486	Tension	F 2y	393
F 2b	3 020	3 280	206	Tension	F 2z	425
F 2c	4 850	5 650	352	Tension		
F 2d	4 430	4 700	287	Tension		
F 3a	7 950	9 400	588	Hor. shear	F 3y	229
F 3b	5 500	5 900	373	Tension	F 3z	171
F 3c	5 780	7 000	448	Crushing		
F 3d	5 100	6 350	403	Hor. shear		
F 4a	6 880	8 600	538	Crushing	F 4y	297
F 4b	6 300	7 600	478	Tension	F 4z	191
F 4c	6 070	7 900	501	Crushing		
F 4d	6 100	7 550	473	Crushing		

TABLE 13. (*Concluded*)

TESTS OF MINOR TEST PIECES.

Stresses are given in lb. per sq. in.

Small Beams, 3 x 3 x 40 inches.					Shear Blocks Approximately 7 x 12 in.	
Des.	Elastic Limit	Fiber Stress	Hor. Shear'g Stress	Manner of Failure	Designation	Shearing Stress
F 9a	8 950	10 510	660	Crushing	F 9y	447
F 9b	6 510	7 840	472	Hor. shear	F 9z	499
F 9c	8 510	9 550	586	Tension		
F 10a	6 670	8 930	558	Hor. shear	F10y	362
F 10b	7 340	7 650	478	Hor. shear	F10z	340
F 10c	5 880	8 540	535	Tension		
F 10d	3 320	5 370	336	Tension		
F 11a	5 930	7 330	443	Tension	F11y	303
F 11b	7 390	8 660	519	Tension	F11z	391
F 11c	6 650	9 470	578	Tension		
F 11d	5 890	6 530	393	Tension		
F 12a	5 940	8 970	549	Tension	F12y	500
F 12b	5 270	6 940	426	Tension	F12z	262
F 12c	5 940	8 420	515	Crushing		
F 12d	5 080	7 600	465	Tension		
F 13a	6 780	9 200	552	Tension	F13y	236
F 13b	5 380	6 930	469	Tension	F13z	342
F 13c	5 690	7 650	470	Tension		
F 13d	6 380	6 620	406	Tension		
F 14a	5 275	6 200	381	Tension	F14y	179
F 14b	5 800	8 850	541	Tension	F14z	222
F 14c	5 640	7 550	463	Tension		
F 14d	5 470	6 670	416	Tension		
F 15a	6 660	6 940	426	Tension	F15y	234
F 15b	6 250	7 520	462	Tension	F15z	273
F 15c	5 830	8 480	521	Crushing		
F 15d	5 460	7 520	472	Tension		
F 16a	5 825	8 270	507	Tension	F16y	320
F 16b	6 270	8 660	513	Crushing	F16z	364
F 16c	6 520	7 570	454	Tension		
F 16d	6 650	6 860	402	Tension		
Av.	5 970	7 445	460			315

difference in depth in Series A and B, and the small number of pieces in some of the series. Reference to this table will be made in the discussion which follows.

18. *Test Data of Miscellaneous Test Pieces. Series M and N.*—In Table 15 are given the data of the tests of series M. The test pieces were taken from four stringers, and by an oversight all pieces were creosoted. However, the results are of some interest in showing the variations in test pieces cut from the same stringer and in the averages for the several stringers. The individual variations in the small beams, both in elastic limit and in

TABLE 14.

SUMMARY OF RESULTS OF TESTS.

All stresses are given in lb. per sq. in.

	Series A Longleaf Pine	Series B Longleaf Pine	Series C				Series D Loblolly Pine		Series E Old Douglas Fir	Series F New Douglas Fir
			Shortleaf Pine		Loblolly Pine					
			Un-treated	Creo-soted	Un-treated	Creo-soted	Un-treated	Creo-soted		
Number of stringers tested	20	14	4	8	4	8	14	12	12	16
Percentage of horizontal shear failures	60	93	100	75	75	62	50	25	83	69
Percentage of tension and compression failures	40	7	0	25	25	38	50	75	17	31
Average horizontal shearing stress at failure	344	386	364	302	368	257	289	330	291	315
Average fiber stress at elastic limit	4336	4392	4343	3386	4164	2330	2960	3587	3823	3955
Average fiber stress at failure	5308	5470	4886	4078	4936	3446	4090	4748	4284	4544
Failing by horizontal shear:										
Average horizontal shearing stress at failure	370	390	364	302	379	273	314	363	298	323
Lowest horizontal shearing stress at failure	188	237	293	224	368	224	253	320	221	275
Highest horizontal shearing stress at failure	497	474	505	410	388	368	381	391	383	401
Average fiber stress at failure	5527	5483	4886	4082	5082	3687	4387	5193	4403	4751
Lowest fiber stress at failure	2640	3620	4005	3025	4890	3020	3760	4460	3320	3990
Highest fiber stress at failure	7260	6540	6810	5550	5195	4915	5740	6020	5730	6040
Failing by tension or compression:										
Average horizontal shearing stress at failure	306	344		302	334	229	263	319	252	293
Highest horizontal shearing stress at failure	471	344		357	334	243	326	420	282	355
Average fiber stress at failure	4978	5300		4067	4500	3043	3794	4600	3690	4088
Lowest fiber stress at failure	2860	5300		3405	4500	2870	2530	2660	3260	3250
Highest fiber stress at failure	8410	5300		4730	4500	3175	5130	6080	4120	5180
Small beams. Average horizontal shearing stress	550	513					375	383	570	460
Small beams. Average fiber stress at elastic limit	6835	6110					4485	4945	7145	5970
Small beams. Average fiber stress at failure	8810	8280					6035	6210	9200	7445
Shear blocks. Average shearing stress	466	393					403	441	486	315

ultimate strength, are not large. The variations in strength of shear blocks are more noticeable, ranging from 45% below the average for the stringer to 60% above that average. The values, 1130, 1035, and 1011 lb. per sq. in., are especially high for loblolly pine, and 241 and 244 lb. per sq. in. are low strengths for shear blocks. Of the averages for test pieces from one stringer, the high value for elastic limit and maximum fiber stress in the small beams in M 4, 6215 and 8735 lb., respectively, may be noted, and also the low value for its shear blocks, 442 lb. per sq. in.

In Table 16 are given the data for the tests of Series N. A comparison of the results for the untreated and treated pieces is made under "26. Effect of Creosoting". The general uniformity of the results in the small test beams cut from the same stringer is noticeable. Two low values, N1a4 and N4c4, are shown by the notes to be due to knots and cross grain. The strength of the shear blocks covers a greater range. The high values are 1106, 1004, and 1014 lb. per sq. in. The low values are 217 and 277 lb. per sq. in. The average maximum fiber stress for the small beams in N2 and N3 is high.

19. *Horizontal Shearing Strength.*—Table 17 gives a summary of the results of the failures in horizontal shear. Fig. 8 is given to show the range and the distribution of the results over the field. The large number of failures by horizontal shear and the seemingly low values found for the shearing resistance, as compared with those quoted in books and with the results obtained from small test specimens, are worthy of note. The method of selection of stringers and the variety of conditions represented indicate that the stringers are not unusual lots and that so far as resistance to shear is concerned their general condition may be considered to be similar to that of timber in use. The range of results is from 188 to 497 lb. per sq. in., and the average for the several series runs from 273 to 390 lb. per sq. in. It is worthy of note in this connection that, as a general rule, for the stringers which did not fail in horizontal shear those developing a shearing stress less than the average for the series had defects like knots which obviously were the occasion of the low cross-breaking strength and that those not showing such defects gave shearing stresses not as high as the highest developed in shear failures. It is also interesting to note that in the stringer which developed the highest fiber stress, A17, the break in tension was

TABLE 15.

TESTS OF SERIES M.

All creosoted loblolly pine. All failed in tension. Stresses are given in lb. per sq. in.

Small Beams, 3 x 3 x 40 in.				Shear Blocks Approximately 7 x 12 in.	
Des.	Elastic Limit	Fiber Stress	Hor. Shearing Stress	Des.	Shearing Stress
M 1a1	5 760	8 150	510	M 1b1	1130
M 1a1	3 760	6 850	436	M 1b2	884
M 1a2	6 000	8 850	542	M 1b3	718
M 1a2	5 870	7 700	481	M 1b4	464
M 1a3	5 020	7 000	445	M 1b5	523
M 1a3	5 130	7 060	449	M 1b6	780
M 1a4	4 650	6 480	405	M 1b7	
M 1a4	5 110	7 200	450	M 1b8	464
M 1c1	5 240	7 040	438	M 1b9	746
M 1c1	5 660	7 690	480	M 1b10	582
M 1c2	4 140	6 460	404	M 1b11	
M 1c2	4 270	6 800	424	M 1b12	954
M 1c3	4 750	7 300	446	M 1b13	
M 1c3	4 730	7 750	484	M 1b14	561
M 1c4	5 450	7 400	471		
M 1c4	4 000	6 660	409		
Av.	4 975	7 275	454		710
M 2a1	5 440	7 800	489	M 2b1	863
M 2a1	5 230	8 500	531	M 2b2	955
M 2a2	4 610	6 710	428	M 2b3	664
M 2a2	5 160	6 920	440	M 2b4	682
M 2a3	4 260	5 350	334	M 2b5	766
M 2a3	4 260	5 730	358	M 2b6	
M 2a4	5 040	6 200	394	M 2b7	
M 2a4	4 480	6 380	406	M 2b8	436
M 2c1	5 520	9 280	590	M 2b9	650
M 2c1	6 800	8 550	544	M 2b10	965
M 2c2	5 900	8 270	526	M 2b11	678
M 2c2	5 020	6 280	400	M 2b12	864
M 2c3	5 360	7 100	444	M 2b13	908
M 2c3	4 150	6 530	414	M 2b14	875
M 2c4	5 930	8 310	528		
M 2c4	5 070	6 490	405		
Av.	5 135	7 160	452		775
M 3a1	3 590	4 740	296	M 3b1	646
M 3a1	4 170	5 450	345	M 3b2	766
M 3a2	3 720	5 650	360	M 3b3	478
M 3a2	4 700	5 830	364	M 3b4	465
M 3a3	4 900	4 900	306	M 3b5	297
M 3a3	4 180	4 760	304	M 3b6	343
M 3a4	4 400	6 350	397	M 3b7	761
M 3a4	5 350	7 100	443	M 3b8	562
M 3c1	5 550	7 360	479	M 3b9	467
M 3c1	5 020	5 400	344	M 3b10	
M 3c2	6 890	7 650	478	M 3b11	
M 3c2	4 100	6 770	424	M 3b12	892
M 3c3	5 150	7 280	463	M 3b13	1035
M 3c3	5 540	7 550	490	M 3b14	1011
M 3c4	6 280	7 850	499		
M 3c4	5 130	7 550	481		
Av.	4 915	6 390	405		643

TABLE 15—(*Concluded*)

Tests of Series M.

All creosoted loblolly pine. All failed in tension. Stresses are given in lb. per sq. in.

Small Beams, 3 x 3 x 40 in.				Shear Blocks Approximately 7 x 12 in.	
Des.	Elastic Limit	Fiber Stress	Hor. Shearing Stress	Des.	Shearing Stress
M 4a1	7 450	7 840	490	M 4b1	358
M 4a1	6 150	7 060	450	M 4b2	241
M 4a2	6 800	7 960	498	M 4b3	496
M 4a2	6 150	7 600	474	M 4b4	276
M 4a3	5 670	7 850	498	M 4b5	244
M 4a3	5 550	9 790	612	M 4b6	281
M 4a4	7 850	10 140	645	M 4b7	460
M 4a4	5 960	8 120	516	M 4b8	480
M 4c1	5 760	8 840	564	M 4b9	740
M 4c1	6 530	9 860	616	M 4b10	563
M 4c2	5 080	7 800	486	M 4b11	
M 4c2	6 410	8 810	563	M 4b12	
M 4c3	6 790	10 400	650	M 4b13	626
M 4c3	4 800	8 800	550	M 4b14	541
M 4c4	6 800	9 460	591		
M 4c4	5 690	9 390	586		
Av.	6 215	8 735	549		442

followed so quickly by horizontal shear failure that only direct observation at the instant of failure enabled the initial cause of failure to be known. Only three beams developed a higher shearing resistance than this, and their failures were by horizontal shear.

It is of interest to compare the shearing resistance developed in the stringers with the results of the shear tests of blocks cut from the stringers. These shear blocks were the full thickness of the stringer and were taken from the mid-depth at an uninjured end. Thus, although they represented the portion of the depth which received the greatest shearing stress, in the case of stringers which had failed by shear, the blocks presumably had greater shearing strength than had the timber at the end which failed. As the shear blocks contained seasoning checks and other defects, the results may be expected to be less than those which would be obtained from small pieces of selected wood or from pieces taken away from the heart wood. Table 18 gives the ratio of the horizontal shearing stress developed in the stringers to the shearing stress developed in the shear blocks. It will be seen that this ratio, in the case of stringers failing in horizontal

TABLE 16.

TESTS OF SERIES N.

Loblolly pine. Even numbers are creosoted. Odd numbers are untreated. Stresses are given in lb. per sq. in.

Small Beams, 3 x 3 x 40 inches.					Shear Blocks Approximately 7 x 12 in.	
Des.	Elastic Limit	Fiber Stress	Hor. Shear'g Stress	Manner of Failure	Des.	Shearing Stress
N1a1	5 060	7 960	498	Tension	N1b1	956
N1a1	4 780	7 950	477	No break	N1b2	841
N1a2	3 600	6 020	376	Tension	N1b3	
N1a2	4 000	5 020	314	Tension	N1b4	757
N1a3	5 490	7 350	459	Tension	N1b5	803
N1a3	4 540	7 760	485	Tension	N1b6	920
N1a4	4 400	5 750	367	Tension	N1b7	878
N1a4	2 350	2 350*	156	Tension	N1b8	696
N1c1	3 840	8 550	545	Tension	N1b9	1106
N1c1	4 480	6 280	400	Tension	N1b10	709
N1c2	4 130	6 040	385	Tension	N1b11	
N1c2	4 260	6 400	400	Tension	N1b12	889
N1c3	4 575	7 550	482	Tension	N1b13	
N1c3	6 660	9 600	600	Tension	N1b14	1004
N1c4	3 780	5 550	353	Tension	N1b15	968
N1c4	3 770	6 720	429	Tension	N1b16	935
Average Untreated	4 930	7 875	493			942
Average Creosoted	3 785	5 480	348			844
N2a1	7 900	11 400	714	Tension	N2b1	671
N2a1	7 460	11 300	706	Tension	N2b2	715
N2a2	5 750	8 310	530	Crushing	N2b3	
N2a2	6 790	8 820	552	Tension	N2b4	611
N2a3	6 150	9 520	607	Tension	N2b5	904
N2a3	6 550	9 800	612	Tension	N2b6	692
N2a4	5 960	7 850	500	Tension	N2b7	865
N2a4	4 790	6 670	425	Tension	N2b8	672
					N2b9	827
					N2b10	552
N2c2	5 520	8 580	546	Tension	N2b11	
N2c2	8 540	10 900	655	Tension	N2b12	632
N2c3	5 790	8 630	550	Tension	N2b13	745
N2c3	6 550	9 080	578	Tension	N2b14	594
N2c4	5 300	8 200	524	Tension	N2b15	737
N2c4	4 230	5 950	379	Tension	N2b16	755
Average Untreated	6 730	9 955	628			791
Average Creosoted	5 860	8 160	514			653
N3a1	6 650	10 040	640	Tension	N3b1	612
N3a1	6 420	8 550	545	Tension	N3b2	739
N3a2	5 220	7 600	475	Tension	N3b3	794
N3a2	5 340	9 420	600	Tension	N3b4	791
N3a3	6 380	10 200	639	Tension	N3b5	877
N3a3	6 000	9 750	609	Tension	N3b6	775
N3a4	4 740	7 100	452	Tension	N3b7	451
N3a4	5 650	8 090	515	Tension	N3b8	517

* Low value is due to knots and cross grain.

TABLE 16. (*Concluded*)

TESTS OF SERIES N.

Loblolly pine. Even numbers are creosoted. Odd numbers are untreated. Stresses are given in lb. per sq. in.

Small Beams, 3 x 3 x 40 inches.					Shear Blocks Approximately 7 x 12 in.	
Des.	Elastic Limit	Fiber Stress	Hor. Shear'g Stress	Manner of Failure	Des.	Shearing Stress
N3c1	6 925	10 800	688	Tension	N3b9	718
N3c1	5 650	9 760	622	Tension	N3b10	277
N3c2	4 810	7 270	464	Crushing	N3b11	423
N3c2	6 400	8 810	562	Tension	N3b12	634
N3c3	5 930	9 450	615	Tension	N3b13	....
N3c3	6 040	8 580	546	Tension	N3b14	617
N3c4	5 250	7 400	462	Tension	N3b15	714
N3c4	5 560	8 190	521	Crushing	N3b16	831
Average Untreated	6 250	8 640	613			656
Average Creosoted	5 370	7 985	506			648
					N4b1	626
					N4b2	717
N4a2	5 780	8 150	520	Tension	N4b3	644
N4a2	6 170	8 760	558	Tension	N4b4	633
N4a3	6 150	9 100	580	Tension	N4b5	528
N4a3	6 460	9 600	625	Crushing	N4b6	524
N4a4	5 180	7 000	446	Tension	N4b7	792
N4a4	5 150	7 210	460	Tension	N4b8	425
N4c1	4 660	8 000	500	Tension	N4b9	858
N4c1	4 860	8 040	512	Tension	N4b10	1014
N4c2	3 840	5 570	355	Tension	N4b11	922
N4c2	3 540	6 280	385	Tension	N4b12	922
					N4b13	....
N4c4	3 520	5 910	377	Tension	N4b14	807
N4c4	2 860	3 240*	198	Tension	N4b15	678
					N4b16	217
Average Untreated	5 530	8 685	554			721
Average Creosoted	4 505	6 515	412			656

* Low value is due to knots and cross grain.

shear, ranged from 0.61 for Series E to 1.00 for Series F. It seems evident that a lower shearing resistance may be expected in beams than will be developed in shear tests on blocks taken as these were.

Attention is called to the higher shearing stresses developed in the small beams taken from the top and bottom of the tested stringers, as shown in Table 13, even when the failure was by tension or compression, and to the fact that the shearing stress developed in the small beams averaged higher than the shearing strength

TABLE 17.

SUMMARY OF FAILURES IN HORIZONTAL SHEAR.

Stresses are given in lb. per sq. in. In the last column is given the highest value for stringers which did not fail by horizontal shear.

Series and Kind	No. of Pieces	Horizontal Shearing Stress			Highest Stress in other Stringers
		Average	Highest	Lowest	
A Untreated longleaf pine	12	370	497	188	471
B Untreated longleaf pine	13	390	474	237	344
C Untreated shortleaf pine	4	364	505	293	...
C Creosoted shortleaf pine	6	302	410	224	357
C Untreated loblolly pine	3	379	388	368	334
C Creosoted loblolly pine	5	273	368	224	243
D Untreated loblolly pine	7	314	381	253	326
D Creosoted loblolly pine	3	363	391	320	420
E Old Douglas fir	10	298	383	221	282
F New Douglas fir	11	323	401	275	355

TABLE 18.

RELATION OF HORIZONTAL SHEARING STRESS DEVELOPED IN STRINGERS TO STRESS DEVELOPED IN SHEAR BLOCKS CUT FROM UNINJURED PORTION OF STRINGERS.

Stresses are given in lb. per sq. in.

Series and Kind	Stringers Failing in Shear				All Stringers			
	No. of Pieces	Hor. Shearing Stress			No of Pieces	Hor. Shearing Stress		
		Stringers	Blocks	Ratio		Stringers	Blocks	Ratio
A Untreated longleaf pine	12	370	491	.75	20	344	466	.74
B Untreated longleaf pine	13	390	394	.99	14	386	393	.98
D Untreated loblolly pine	7	314	384	.82	14	289	403	.72
D Creosoted loblolly pine	3	363	483	.75	12	330	441	.75
E Old Douglas fir	10	298	491	.61	12	291	486	.60
F New Douglas fir	11	323	321	1.01	16	315	315	1.00

of the shear block taken from the same stringer except for Series D which was loblolly pine having a low fiber strength and hence developing a correspondingly low shearing stress in the beams tested. This comparison brings out the greater shearing resistance of the wood at the top and bottom of the stringer in timber subject to seasoning checks of magnitude.

In examining the results of these tests it is apparent that seasoning checks are a source of weakness in horizontal shearing

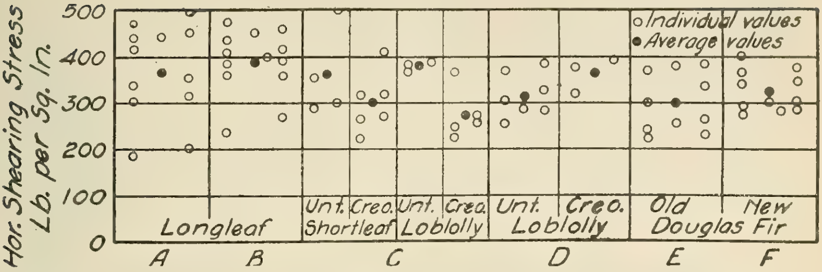

Fig. 8. Values of Horizontal Shearing Stress in Beams Failing in Horizontal Shear.

resistance and that a wood which develops marked seasoning checks, as longleaf pine, may have its higher tensile and compressive strength discounted by shearing weaknesses, while a softer wood like loblolly pine in beams of the dimensions used in stringers may more advantageously utilize the fiber strength it possesses. It is well to emphasize the importance of using methods of seasoning which will minimize the evil of the checks and cracks produced in seasoning.

As having a possible bearing on whether the greater exposure at the end of the stick may develop more troublesome seasoning checks than are developed in the remainder of the stick, the tests of the Douglas fir stringers may be examined. These stringers came in lengths of 32 ft. and were cut at the middle to make two test beams, thus giving one old end and one new end. Of the old Douglas fir which failed in horizontal shear, six failed at the new end and two at the old end, and for the other two there is no record. Of the new Douglas fir which failed in horizontal shear, two failed at the new end and seven at the old end, and for two there is no record.

20. *Maximum Fiber Stress.*—The maximum fiber stress developed in the full-size beams was generally low, lower than the values generally quoted for the strength of such timber. The shear failures, of course, operated to prevent the development of the full fiber strength of the wood, but it is worthy of note (see Table 14) that in every series the average value of the fiber stress developed in beams failing in tension was less than the average in beams failing in horizontal shear, and that with the exception of Series A the highest fiber stress developed was less in the tension failures than in the shear failures. That the reason for

low fiber strength may lie principally in the presence of knots and cross-grain emphasizes rather than detracts from the importance of these deductions.

The average value of the maximum fiber stress is, in the several series, from 3445 lb. per sq. in. in the creosoted loblolly pine of Series D to 5470 lb. per sq. in. in the longleaf pine of Series A. The high values, as may be expected, are generally in clear, straight-grained heavy sticks, though A17 which developed a maximum fiber stress of 8410 lb. per sq. in., the highest strength of any beam tested, contained a number of solid knots, ¾ in. to 1¾ in. across, all at or near the upper surface of the beam. The low values in cross-breaking failures were found in sticks having defects like large knots, cross grain, or in the case of the loblolly pine a large amount of sap wood. In most of the very low values in cross breaking the defects in the sticks were quite apparent, as in the two sticks in Series C which were selected to show the effect of large knots and as in D 5 and D 16 which would hardly be called merchantable sticks, but in A 4 (see Plate 1) the bad shake through the middle of the length of the beam could not have been known in advance of the test.

Tests show that selected wood is stronger and stiffer in tension than in compression, but it is seen that the failures in cross bending were generally on the tension side. The exceptions are in the creosoted loblolly in Series D. It will be shown that in Series C the deformation on the tension face of the beams was greater than on the compression face. These facts seem to indicate that the defects of knots and cross grain have a greater effect on the properties of tension than on those of compression. Possibly another explanation may be found for the conditions in loblolly pine.

Fig. 9 shows for the several series the distribution of the maximum fiber stress developed, a distinction being made between cross-breaking and shear failures.

21. *Relation of Fiber Stress of Small and Full-size Pieces.*—It is evident from Table 19 that the small test beams taken from the top and bottom of the full-size stringers developed much higher stresses than were developed in the tests of the stringers. This was true in the fiber strength of the small test beams which failed in tension or compression and also in the shearing strength developed in the beams failing in horizontal shear. The higher fiber

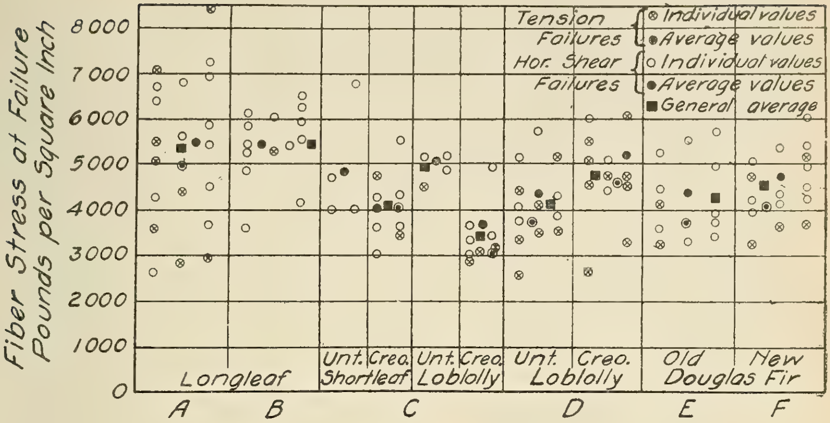

FIG. 9. VALUES OF FIBER STRESS AT FAILURE.

stress developed in the small beams may be due in part to the greater freedom from knots in the small test beams selected than in the large stringers, but a large part may be attributed to greater homogeneity of structure in the small beams and to the absence of seasoning checks. The higher horizontal shearing stress developed in the small beams may be due principally to the greater freedom from seasoning checks and the consequent greater resistance of the fibers to longitudinal shear.

The comparison of the fiber stresses developed in cross bending at failure given in Table 19 shows that the fiber stress of the full-size stringers averaged in the several series from 48% to 76% of the fiber stress in the corresponding small test beams. Even with the failures by horizontal shear excluded from consideration, the relation would be but little better. In Series C a systematic test of small beams was not made, but the small beams taken from four of the full-size beams showed the latter to have 47% to 55% of the strength of the former in the case of the shortleaf pine and 76% to 83% in the case of the loblolly pine. Few of the small test beams failed by horizontal shear, but the shearing strength developed in the small beams was much higher than in the large ones.

The results of the tests as a whole go to show, if it were necessary to have a new confirmation of this, that the strength of small pieces may not be taken as representative of the strength of full-size sticks. Tests of small pieces may be of service in comparing woods of different kinds, though even here one species or

TABLE 19.

RELATION OF MAXIMUM FIBER STRESS DEVELOPED IN STRINGERS TO STRESS DEVELOPED IN SMALL TEST BEAMS.

Stresses are given in lb. per sq. in.

Series and Kind	Average			Highest			Lowest		
	Large	Small	Ratio	Large	Small	Ratio	Large	Small	Ratio
A Unt. longleaf pine....	5308	8810	.60	8410	11500	.73	2640	10000	.26
B Unt. longleaf pine....	5470	8280	.66	6470	9850	.66	3620	7410	.49
D Unt. loblolly pine....	4090	6035	.68	5740	8450	.68	2530		
D Creo. loblolly pine...	4748	6210	.76	6080	9000	.68	2660	1880	1.42
E Old Douglas fir.......	4284	9200	.47	5730	10950	.52	3260	5300	.62
F New Douglas fir......	4544	7445	.61	6040	10510	.57	3250		

one shipment may be more subject to the weakness of knots, shakes, or seasoning checks than another. The high values of fiber strength and of horizontal shearing strength sometimes given in tables in engineering books and literature seem to have crept in through assuming that the strength of small test-pieces represents the strength of the full-size stick which would be used.

22. *Elastic Limit.*—Table 20 gives the fiber stress at the elastic limit and the ratio of this stress to the stress at the ultimate. Failures by horizontal shear are grouped separately from cross-breaking failures, the former preceding the latter in the table. There is a considerable range in the value of the elastic limit. In Series C the range is from 1960 to 5830 lb. per sq. in.; in Series D from 1460 to 4330 lb. per sq. in. The elastic limit is evidently affected by defects like knots and cross grain. To what extent it is affected by conditions, like seasoning checks, which give low horizontal shearing strength or act to permit considerable longitudinal movement of fibers, is not known. The ratio of the elastic limit to the breaking strength is given in the column of ratios in Table 20. The average of the ratios is from 0.67 to 0.90.

Fig. 10 shows for the several series the elastic limits developed. It shows graphically the distribution of individual values over the field.

23. *Deflection of Beams and Modulus of Elasticity.*—The deflections at mid-span are shown in the diagrams in Fig. 11 to 19 at the end of the text. Since stringers are usually placed side by side, their relative stiffness fixes the proportion of the total load which the individual stringer takes; i. e., for a given deflection the stiffer stringer takes the larger share of the load and the less

TABLE 20.

RELATION OF FIBER STRESS AT ELASTIC LIMIT TO FIBER STRESS AT FAILURE.

Stresses are given in lb. per sq. in.

Des.	Elastic Limit	Ratio to Maximum	Des.	Elastic Limit	Ratio to Maximum	Des.	Elastic Limit	Ratio to Maximum
A 1	1960	.74	C 5	3165	.87	D 20	4330	.97
A 2	3060	.68	C 6	3620	.84	D 21	4280	.71
A 3	5480	.93	C 7	2360	.64	D 23	4510	.88
A 5	4820	.86	C 8	4065	.94		—	—
A 7	3890	.90	C 9	2715	.90	Av.	4373	.85
A 8	5630	.84	C 12	4970	.90			
A 11	5720	.84		—	—	D 15	3680	.78
A 12	5700	.82	Av.	3482	.85	D 16	1460	.55
A 13	5440	.75				D 17	3530	.70
A 15	3610	.98	C 10	3660	.77	D 18	3600	.72
A 18	5200	.81	C 11	2530	.74	D 19	4020	.66
A 20	5310	.97		—	—	D 22	3570	.65
	—	—	Av.	3095	.76	D 24	4180	.92
Av.	4652	.84				D 25	2500	.76
			C 13	3900	.76	D 26	3380	.74
A 4	3150	.88	C 15	3940	.80		—	—
A 6	2570	.90	C 16	4900	.94	Av.	3324	.72
A 9	4060	.74		—	—			
A 10	2940	1.00	Av.	4247	.83	E 1	3050	.92
A 14	3010	.68				E 2	5360	.97
A 16	5830	.83	C 14	3915	.87	E 3	4970	.94
A 17	5800	.69		—	—	E 4	3260	.86
A 19	3540	.70	Av.	3915	.87	E 5	3160	.92
	—	—				E 6	3490	.97
Av.	3862	.80	C 17	2710	.79	E 7	2960	.76
			C 18	2155	.64	E 9	5090	.89
B 1	4180	.86	C 19	2670	.72	E 11	4660	.94
B 2	5020	.85	C 20	2180	.72	E 12	3500	.78
B 3	5080	.81	C 24	2795	.57		—	—
B 4	5160	.95		—	—	Av.	3950	.90
B 5	4560	.74	Av.	2502	.69			
B 6	5110	.84				E 8	4120	1.00
B 7	4150	.79	C 21	1930	.67	E 10	2260	.69
B 8	3720	.68	C 22	2180	.69		—	—
B 9	3440	.95	C 23	2018	.66	Av.	3190	.84
B 10	4720	.72		—	—			
B 11	3960	.95	Av.	2043	.67	F 1	3730	.88
B 12	4860	.81				F 2	3420	.86
B 13	3970	.71	D 1	3820	.74	F 3	3940	.93
	—	—	D 4	3730	.65	F 4	3410	.82
Av.	4456	.82	D 9	3370	.87	F 5	4980	.98
			D 10	2950	.78	F 6	4890	.98
B 14	3560	.67	D 12	2940	.72	F 9	4700	.78
	—	—	D 13	3100	.72	F 11	4080	.90
Av.	3560	.67	D 14	3320	.88	F 12	4250	.80
				—	—	F 13	4020	.92
C 1	....	....	Av.	3320	.77	F 15	4370	.81
C 2	3780	.94					—	—
C 3	4310	.91	D 2	2790	.68	Av.	4163	.88
C 4	4940	.72	D 3	2180	.65			
	—	—	D 5	1950	.77	F 7	2920	.79
Av.	4343	.86	D 6	2160	.61	F 8	2550	.78
			D 7	3660	.71	F 10	3180	.87
			D 8	2620	.75	F 14	4280	.91
			D 11	2830	.64	F 16	4560	.88
				—	—		—	—
			Av.	2598	.69	Av.	3498	.85

stiff stringer receives a smaller share. In the several series the stiffness of the beams (a property which may be considered to vary as the reciprocal of the modulus of elasticity) ranged from, say, 0.75 of the average stiffness for the series to, say, 1.25 times the average stiffness. A weak stringer, if placed beside an average stringer of its kind, would then take 75% of the load carried by the average stringer, or 86% of its half of the load. A stiff stringer, if placed beside an average stringer of its kind, would take 125% of the load carried by the average stringer, or 111% of its half of the load. As the tests show that the stringers with low carrying strength were generally less stiff than the strongest sticks, this variation may be considered to be helpful when sticks having defects are placed beside good timber. A 6, C 11, D 5, and D 16 may be cited as examples where large knots and poor grain acted to give low stiffness and low strength. The stiffness of A 6 was only 67% of the average of its series, and D 16 only 47%.

The modulus of elasticity of the full-size beams is given in Table 21. It was calculated from the deflection for the straight portion of the deflection curve, using the formula for center deflection, $\frac{23}{1296}\frac{Wl^3}{EI}$, given on page 7. The extremely low values are in sticks having large knots and cross grain. With the exception of a few values, the modulus of elasticity in each series is fairly uniform.

In the tests in Series C the deformation of the top and the bottom fiber along the middle of the beam was measured, as already described. The fiber stress was calculated by the usual beam formula, and from this calculated fiber stress and the measured deformations the modulus of elasticity for the top and bottom fiber was calculated. The results are given in Table 22, together with the modulus of elasticity determined from the deflections. In making comparisons it must be borne in mind that the formula for fiber stress and that for deflection are based upon the assumption of a uniform and homogeneous beam and also that the horizontal shearing deformations are neglected. The modulus of elasticity obtained from the deformation of the bottom fiber averages somewhat less than that obtained from the deformation of the top fiber, and the average modulus of elasticity obtained from the deflections is markedly less than either. It would be interesting to know what part of this difference is due to horizontal shearing action and what part to variability of the wood from heart to outer fiber.

Table 23 gives the modulus of elasticity of the small beams taken from the stringers of Series A, B, D, E, and F. The

TABLE 21.

MODULUS OF ELASTICITY OF TIMBER STRINGERS.

Values are given in lb. per sq. in.

Series A		Series B		Series C		Series C		Series D		Series D		Series E		Series F	
Des.	E	Des.	E	Des.	E	Des.	E	Des.	E	Des.	E	Des.	E	Des.	E
A 1	1 795 000	B 1	1 378 000	C 1	1 590 000	C 13	1 590 000	D 1	1 406 000	D 15	1 386 000	E 1	1 310 000	F 1	1 274 000
A 2	1 894 000	B 2	1 694 000	C 2	1 595 000	C 14	1 474 000	D 2	1 327 000	D 16	611 000	E 2	2 050 000	F 2	1 143 000
A 3	1 653 000	B 3	1 636 000	C 3	1 595 000	C 15	1 645 000	D 3	1 186 000	D 17	1 294 000	E 3	2 087 000	F 3	1 650 000
A 4	1 461 000	B 4	2 105 000	C 4	1 585 000	C 16	1 570 000	D 4	1 915 000	D 18	1 377 000	E 4	1 840 000	F 4	1 618 000
A 5	1 610 000	B 5	2 000 000					D 5	944 000	D 19	1 677 000	E 5	1 684 000	F 5	1 900 000
A 6	1 025 000	B 6	1 615 000	Av.	1 591 000	Av.	1 570 000	D 6	1 068 000	D 20	1 193 000	E 6	1 700 000	F 6	1 716 000
A 7	1 696 000	B 7	1 538 000					D 7	1 428 000	D 21	1 410 000	E 7	1 900 000	F 7	1 325 000
A 8	1 480 000	B 8	1 475 000	C 5	1 224 000	C 17	1 150 000	D 8	1 070 000	D 22	1 857 000	E 8	1 852 000	F 8	1 138 000
A 9	1 473 000	B 9	1 706 000	C 6	1 325 000	C 18	1 060 000	D 9	1 500 000	D 23	1 657 000	E 9	1 785 000	F 6	1 615 000
A 10	1 238 000	B 10	1 878 000	C 7	1 045 000	C 19	1 090 000	D 10	1 523 000	D 24	1 582 000	E 10	1 426 000	F 10	1 582 000
A 11	1 914 000	B 11	1 518 000	C 8	1 350 000	C 20	1 130 000	D 11	1 180 000	D 25	940 000	E 11	1 990 000	F 11	1 610 000
A 12	1 620 000	B 12	1 577 000	C 9	1 225 000	C 21	975 000	D 12	1 363 000	D 26	1 368 000	E 12	1 733 000	F 12	1 495 000
A 13	1 725 000	B 13	1 618 000	C 10	1 300 000	C 22	1 030 000	D 13	1 367 000					F 13	1 542 000
A 14	1 472 000	B 14	1 304 000	C 11	887 000	C 23	1 132 000	D 14	1 386 000					F 14	1 400 000
A 15	1 714 000			C 12	1 478 000	C 24	1 095 000							F 15	1 461 000
A 16	1 842 000													F 16	1 510 000
A 17	1 596 000			Av.	1 229 000	Av.	1 083 000								
A 18	1 704 000														
A 19	1 216 000														
A 20	1 810 000														
Av.	1 597 000	Av.	1 648 000					Av.	1 333 000	Av.	1 363 000	Av.	1 780 000	Av.	1 499 000

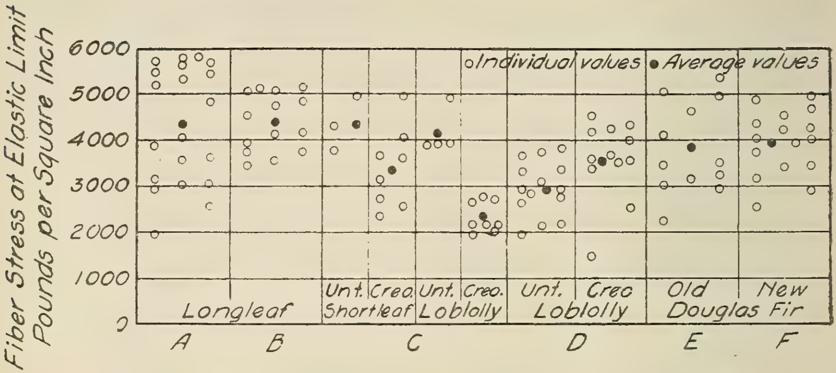

FIG. 10. VALUES OF FIBER STRESS AT ELASTIC LIMIT.

values are calculated from the center deflections, typical load-deflection diagrams being given in Fig. 20 to 23. The very low values of the modulus of elasticity are in beams having knots. It is seen that the averages are a very little lower than those found for the full-size beams.

Table 24 gives the modulus of elasticity of the small beams of Series M and N calculated from the center deflections.

24. *Effect of Knots and Other Defects.*—Certain statements bearing on the influence of knots upon the strength and manner of failure of timber beams, which are apparent from a study of the general properties of wood, are confirmed by these tests. The presence of small knots along or near the neutral axis, especially toward the ends of the beam, increases the resistance to horizontal shear. Seasoning checks do not form to the same extent nor are they continuous for so great a distance in wood having knots so located, and a shear failure passes around such knots and makes a jagged and irregular break. The presence of larger knots along the middle of the beam, located in such a way that their influence (i. e., with reference to the direction of the grain) does not extend into the lower or upper one-third of the depth of the beam, is not especially injurious. It is important to note, however, that knots located in the lower quarter or upper quarter of the beam and within the portion of the length which has the maximum bending moment, as for example the middle third in beams loaded at the one-third points, decrease the carrying strength of the beam very markedly and constitute a serious defect. The defect has greater influence when the knot carries with it a considerable change of

TABLE 22.

Moduli of Elasticity Calculated from Deformations and Deflections.

The modulus of elasticity was calculated, (1) from the deformation on the compression side, (2) from the deformation on the tension side, (3) from the deflection of the stringer.

Des.	Modulus of Elasticity lb. per sq. in.			Description
	(1) Top Fiber	(2) Bottom Fiber	(3) Deflection	
C 1	1 930 000	1 765 000	1 590 000	Untreated shortleaf pine.
C 2	1 925 000	1 650 000	1 595 000	Untreated shortleaf pine.
C 3	2 130 000	2 400 000	1 595 000	Untreated shortleaf pine.
C 4	2 400 000	1 690 000	1 585 000	Untreated shortleaf pine.
Av.	2 096 000	1 876 000	1 591 000	
C 5	1 580 000	1 650 000	1 224 000	Creosoted shortleaf pine.
C 6	1 650 000	1 600 000	1 325 000	Creosoted shortleaf pine.
C 7	1 250 000	1 060 000	1 045 000	Creosoted shortleaf pine.
C 8	1 640 000	1 770 000	1 350 000	Creoseted shortleaf pine.
C 9	1 740 000	1 390 000	1 225 000	Creosoted shortleaf pine.
C 10	1 740 000	1 535 000	1 300 000	Creosoted shortleaf pine.
C 11	1 065 000	963 000	887 000	Creosoted shortleaf pine.
C 12	1 750 000	1 860 000	1 478 000	Creosoted shortleaf pine.
Av.	1 552 000	1 478 000	1 229 000	
C 13	2 440 000	1 830 000	1 590 000	Untreated loblolly pine.
C 14	2 040 000	1 800 000	1 474 000	Untreated loblolly pine.
C 15	2 200 000	2 020 000	1 645 000	Untreated loblolly pine.
C 16	1 695 000	2 140 000	1 570 000	Untreated loblolly pine.
Av.	2 094 000	1 992 000	1 570 000	
C 17	1 960 000	1 430 000	1 150 000	Creosoted loblolly pine.
C 18	1 900 000	....	1 060 000	Creosoted loblolly pine.
C 19	1 530 000	1 170 000	1 090 000	Creosoted loblolly pine.
C 20	1 430 000	1 500 000	1 130 000	Creosoted loblolly pine.
C 21	1 260 000	905 000	975 000	Creosoted loblolly pine.
C 22	1 630 000	1 400 000	1 030 000	Creosoted loblolly pine.
C 23	2 265 000	1 725 000	1 132 000	Creosoted loblolly pine.
C 24	1 226 000	1 175 000	1 095 000	Creosoted loblolly pine.
Av.	1 650 000	1 329 000	1 083 000	

direction of grain on either side and above and below it. Beams A 6 and F 7, Plates 1 and 8 are examples of this. Special care should be given in inspection to throw out sticks in which the size and location of knots are such as to impair the strength of the stick, even if such rejection may increase the cost of the materials. It seems to be true that the influence of knots is less when the stick is placed so that the knot comes on the compression side rather than on the tension side, provided, of course, the knot is solid.

Cross grain is a common defect which seriously impairs the strength of timber. The saw marks may hide the grain. Tension

TABLE 23.

Modulus of Elasticity of Small Beams.

Values are given in lb. per sq. in.

Des.	E	Des.	E	Des.	E	Des.	E
Series A. Untreated Longleaf Pine.							
A 1a	1 665 000	A 6a	1 005 000	A 11a	1 546 000	A 16a	1 570 000
A 1b	1 323 000	A 6b	1 422 000	A 11b	1 750 000	A 16b	1 570 000
A 1c	1 593 000	A 6c	1 333 000	A 11c	1 585 000	A 16c	1 715 000
A 1b	1 642 000	A 6d	1 593 000	A 11d	1 568 000	A 16d	1 800 000
A 2a	2 000 000	A 7a	1 690 000	A 12a	1 641 000	A 17a	1 527 000
A 2b	1 740 000	A 7b	1 735 000	A 12b	1 297 000	A 17b	1 353 000
A 2c	1 960 000	A 7c	1 814 000	A 12c	1 700 000	A 17c	1 567 000
A 2d	1 863 000	A 7d	1 863 000	A 12d	1 470 000	A 17d	1 617 000
A 3a	1 520 000	A 8a	1 347 000	A 13a	1 325 000	A 18a	1 502 000
A 3b	1 616 000	A 8b	883 000	A 13b	1 350 000	A 18b	1 690 000
A 3c	1 460 000	A 8c	1 078 000	A 13c	1 519 000	A 18c	1 420 000
A 3d	1 550 000	A 8d	1 347 000	A 13d	2 035 000	A 18d	1 520 000
A 4a	1 445 000	A 9a	564 000	A 14a	1 645 000	A 19a	1 323 000
A 4b	1 347 000	A 9b	1 433 000	A 14b	1 200 000	A 19b	1 125 000
A 4c	1 010 000	A 9c	1 640 000	A 14c	1 200 000	A 19c	663 000
A 4d	981 000	A 9d	1 246 000	A 14d	1 347 000	A 19d	1 078 000
A 5a	1 078 000	A 10a	1 346 000	A 15a	2 056 000	A 20a	1 593 000
A 5b	1 250 000	A 10b	1 005 000	A 15b	2 155 000	A 20b	1 642 000
A 5c	981 000	A 10c	1 423 000	A 15c	1 567 000	A 20c	1 765 000
A 5d	1 152 000	A 10d	1 294 000	A 15d	1 275 000	A 20d	1 690 000
				Av.		....	1 462 000
Series B. Unseasoned Longleaf Pine.							
B 1b	1 315 000	B 5a	2 060 000	B 8a	1 390 000	B 11b	1 337 000
B 1c	1 170 000	B 5b	2 155 000	B 8b	1 396 000	B 11c	1 723 000
B 2a	1 495 000	B 5c	2 125 000	B 8c	1 565 000	B 11d	1 587 000
B 2b	1 803 000	B 5d	1 867 000	B 8d	1 495 000	B 12a	1 570 000
B 2c	1 386 000	B 6a	1 170 000	B 9a	1 645 000	B 12b	1 380 000
B 2d	1 338 000	B 6b	1 383 000	B 9b	1 705 000	B 12c	1 136 000
B 3a	1 673 000	B 6c	1 705 000	B 9c	1 720 000	B 12d	1 095 000
B 3b	1 433 000	B 6d	1 703 000	B 9d	1 685 000	B 13a	1 338 000
B 3c	1 553 000	B 7a	1 575 000	B 10a	1 540 000	B 13b	1 465 000
B 3d	1 515 000	B 7b	1 450 000	B 10b	1 643 000	B 13c	1 460 000
B 4a	1 895 000	B 7c	1 402 000	B 10c	1 848 000	B 13d	1 617 000
B 4b	2 015 000	B 7d	1 415 000	B 10d	1 630 000	B 14a	1 182 000
B 4c	1 990 000			B 11a	1 385 000	B 14b	1 375 000
				Av.		....	1 558 000
Series D. Creosoted Loblolly Pine.							
D 16a	443 000	D 20a	1 152 500	D 22a	1 495 000	D 24c	1 380 000
D 16d	100 000	D 20b	1 225 000	D 22b	1 643 000	D 24d	1 510 000
D 17a	760 000	D 20c	1 178 000	D 22c	1 593 000	D 25a	1 193 000
D 18a	907 500	D 20d	1 120 000	D 22d	1 567 000	D 25b	1 163 000
D 18c	1 177 000	D 21a	1 030 000	D 23a	1 665 000	D 25c	905 000
D 19a	1 795 000	D 21b	1 380 000	D 23b	1 700 000	D 25d	807 000
D 19b	1 486 000	D 21c	1 303 000	D 23c	1 542 000	D 26a	1 145 000
D 19c	1 120 000	D 21d	1 355 000	D 23d	1 457 000	D 26b	1 505 000
D 19d	1 175 000			D 24a	1 430 000	D 26c	1 225 000
				D 24b	1 565 000	D 26d	1 470 000
				Av.		....	1 260 000

TABLE 23 (*Concluded*)

Modulus of Elasticity of Small Beams

Des.	E	Des.	E	Des.	E	Des.	E
Series D. Untreated Loblolly Pine							
D 1a	1 570 000	D 4a	1 660 000	D 8c	865 000	D 11d	896 000
D 1b	1 340 000	D 4b	1 695 000	D 8d	1 120 000	D 12a	1 225 000
D 1c	1 487 000	D 4c	1 512 000	D 9a	1 396 000	D 12b	1 330 000
D 1d	1 420 000	D 4d	1 405 000	D 9b	1 418 000	D 12c	969 000
D 2a	1 330 000	D 6a	920 000	D 9c	1 280 000	D 12d	1 016 000
D 2b	1 383 000	D 6b	766 000	D 9d	1 112 000	D 13a	1 215 000
D 2c	527 500	D 6c	975 000	D 10a	1 725 000	D 13b	1 150 000
D 2d	1 290 000	D 6d	1 110 000	D 10b	1 485 000	D 13c	1 276 000
D 3b	1 143 000	D 7b	1 720 000	D 10c	1 156 000	D 13d	1 452 000
D 3c	902 500	D 7c	1 153 000	D 10d	1 385 000	D 14a	1 373 000
D 3d	885 000	D 7d	1 600 000	D 11a	1 293 000	D 14b	972 500
		D 8a	997 500	D 11b	1 228 000	D 14c	1 460 000
		D 8b	1 050 000	D 11c	905 000	D 14d	1 465 000
				Av.		......	1 243 000
Series E. Old Douglas Fir							
E 1a	1 897 000	E 4a	1 718 000	E 7a	2 030 000	E 10a	1 610 000
E 1b	1 875 000	E 4b	1 862 000	E 7b	1 875 000	E 10b	817 000
E 1c	1 883 000	E 4c	1 640 000	E 7c	1 563 000	E 11c	1 408 000
E 1d	1 850 000	E 4d	1 845 000	E 7d	1 665 000	E 10d	1 616 000
E 2a	1 850 000	E 5a	1 380 000	E 8a	1 960 000	E 11a	1 490 000
E 2b	2 070 000	E 5b	1 534 000	E 8b	859 000	E 11b	1 618 000
E 2c	1 730 000	E 5c	1 815 000	E 8c	1 650 000	E 11c	1 103 000
E 2d	2 040 000	E 5d	1 800 000	E 8d	1 569 000	E 11d	1 820 000
E 3a	1 765 000	E 6a	1 485 000	E 9a	1 350 000	E 12a	1 448 000
E 3b	1 715 000	E 6c	1 617 000	E 9b	1 442 000	E 12b	1 708 000
E 3c	1 667 000	E 6d	1 690 000	E 9c	1 442 000	E 12c	1 393 000
E 3d	1 650 000			E 9d	1 665 000	E 12d	1 446 000
				Av.		......	1 635 000
Series F. New Douglas Fir							
F 1a	1 195 000	F 4a	1 717 000	F 11a	1 720 000	F 14a	1 250 000
F 1b	1 340 000	F 4b	1 557 000	F 11b	1 505 000	F 14b	1 250 000
F 1c	983 000	F 4c	1 443 000	F 11c	1 755 000	F 14c	1 330 000
F 2a	1 127 000	F 4d	1 470 000	F 11d	1 533 000	F 14d	1 176 000
F 2b	1 010 000	F 9a	1 675 000	F 12a	1 432 000	F 15a	1 485 000
F 2c	882 000	F 9b	1 282 000	F 12b	1 237 000	F 15b	1 406 000
F 2d	1 147 000	F 9c	1 673 000	F 12c	1 567 000	F 15c	1 510 000
F 3a	1 825 000	F 10a	1 765 000	F 12d	1 382 000	F 15d	1 225 000
F 3b	1 366 000	F 10b	1 765 000	F 13a	1 306 000	F 16a	1 562 000
F 3c	1 345 000	F 10c	1 680 000	F 13b	1 487 000	F 16b	1 730 000
F 3d	1 513 000	F 10d	1 176 000	F 13c	1 328 000	F 16c	1 363 000
				F 13d	1 276 000	F 16d	1 250 000
				Av.		......	1 413 000

TABLE 24.

Modulus of Elasticity of Small Beams, Series M and N.

Des.	E	Des.	E	Des.	E	Des.	E
Series M. Creosoted Loblolly Pine.							
M1a1	1 258 000	M2a1	1 565 000	M3a1	1 128 000	M4a1	1 440 000
M1a1	1 065 000	M2a1	1 476 000	M3a1	1 075 000	M4a1	1 445 000
M1a2	1 470 000	M2a2	1 075 000	M3a2	1 120 000	M4a2	1 470 000
M1a2	1 260 000	M2a2	1 188 000	M3a2	1 070 000	M4a2	1 560 000
M1a3	1 190 000	M2a3	1 275 000	M3a3	1 058 000	M4a3	1 387 000
M1a3	1 295 000	M2a3	982 000	M3a3	932 000	M4a3	1 607 000
M1a4	1 225 000	M2a4	1 213 000	M3a4	884 000	M4a4	1 540 000
M1a4	1 187 000	M2a4	1 214 000	M3a4	1 262 000	M4a4	1 415 000
M1c1	1 082 000	M2c1	1 110 000	M3c1	1 128 000	M4c1	1 466 000
M1c1	1 225 000	M2c1	1 176 000	M3c1	987 000	M4c1	1 470 000
M1c2	1 066 000	M2c2	1 386 000	M3c2	1 320 000	M4c2	1 372 000
M1c2	1 225 000	M2c2	1 437 000	M3c2	1 248 000	M4c2	1 316 000
M1c3	1 340 000	M2c3	1 392 000	M3c3	1 314 000	M4c3	1 538 000
M1c3	1 115 000	M2c3	1 223 000	M3c3	1 303 000	M4c3	1 715 000
M1c4	1 110 000	M2c4	1 445 000	M3c4	1 200 000	M4c4	1 715 000
M1c4	1 052 000	M2c4	1 017 000	M3c4	1 190 000	M4c4	1 568 000
				Av.			1 275 000
Series N. Loblolly Pine.							
Untreated				Creosoted			
N1c1	752 000	N3c3	1 225 000	N1c2	747 500	N3c2	1 305 000
N1c1	692 500	N3c3	1 188 000	N1c2	784 500	N3c2	1 268 000
N1c3	907 000	N3a1	1 304 000	N1c4	794 000	N3c4	1 323 000
N1c3	858 000	N3a1	1 213 000	N1c4	872 500	N3c4	1 297 000
N1a1	735 000	N3a3	1 495 000	N1a2	736 000	N3a2	1 260 000
N1a1	807 500	N3a3	1 530 000	N1a2	736 000	N3a2	1 304 000
N1a3	1 055 000	N4c1	735 000	N1a4	849 000	N3a4	1 043 000
N1a3	796 000	N4c1	925 000	N1a4	566 000	N3a4	1 133 000
N2c3	1 212 000	N4a3	1 380 000	N2c2	1 223 000	N4c2	693 000
N2c3	1 223 000	N4a3	1 415 000	N2c2	1 460 000	N4c2	1 020 000
N2a1	1 568 000			N2c4	1 200 000	N4c4	1 130 000
N2a1	1 653 000			N2c4	1 040 000	N4c4	739 000
N2a3	1 293 000			N2a2	1 500 000	N4a2	1 270 000
N2a3	1 345 000			N2a2	1 470 000	N4a2	1 333 000
N3c1	1 570 000			N2a4	1 382 000	N4a4	1 165 000
N3c1	1 300 000			N2a4	1 076 000	N4a4	1 178 000
Av.			1 161 000	Av.			1 091 000

breaks at low loads in full-size sticks may frequently be traced to cross grain.

Shakes and seasoning checks are deleterious to horizontal shearing strength. A shake in the lower or upper portion may cause failure in tension or compression or a combination of one of these with shear failure. The liability of a wood to check during the time of seasoning has then an important bearing upon its desirability.

That knots and cross grain contributed largely to the weakness of the timber is seen in looking over the results, although it should be noted that in most of the stringers the defects were not such as to have caused rejection under ordinary inspection. In Series A, nearly every piece which failed in tension had knots and cross grain. A 6 and A 10 (Plates 1 and 2) are good examples, particularly of the low strength which may result from such defects. The stringer A 6 had been selected as an example of knots which were plain cause for rejection. In Series C four sticks failing in tension gave low values, due to knots and cross grain. In Series D, six sticks showing bad knots and cross grain failed in tension. In the same way the fir stringers failing by tension at low loads contained knots and showed cross grain. All of these, however, would be called good sticks. A 4 is an example of a defect of another kind causing tension failure, in this case a hidden defect, as the shake was not visible externally. The seasoning check in A 1 along which it failed by horizontal shear at a very low load was conspicuous; but horizontal shear did not always occur along seasoning checks which seemed the most important, and some sticks, as B 11, which were fairly free from seasoning checks, failed by horizontal shear. C 9 and D 14 are examples of cross grain affecting the horizontal shearing strength. A study of the views given in the Plates 1 to 16 will indicate something of the size and position of defects.

25. *Relation of Depth to Length.*—It is evident that for stated values of the modulus of rupture and of the longitudinal shearing stress in a beam, a ratio of length of span to depth of stringer will exist for which the stringer is as likely to fail in cross bending as in horizontal shear. Thus, for a modulus of rupture of 5000 lb. per sq. in. and a horizontal shearing stress of 300 lb. per sq. in., using one-third point loading, a span twelve and one-half times its depth will give the two stresses simultaneously. This makes a depth of 13 in. for a span of 13½ ft. If instead of the modulus of rupture the elastic limit be used, say, 3000 lb. per sq. in., and if for the elastic limit or yield point of the horizontal shearing strength 300 lb. per sq. in. be taken, the resulting ratio is 7½. This would correspond to a depth of 21.6 in. for a span of 13½ ft. For the first-named values, the carrying strengths of beams of depths greater than 13 in. would increase only as the depth of beam; for the latter, depths less than 21.6 in. would not fail in

horizontal shear before the elastic limit of the material was reached. It may be well to find whether the tests bear out such reasoning and whether other conditions may not cover up the influence of such a comparison.

In Table 8 are given values for longleaf pine for depths of 12, 14 and 16 inches. It is plain that the small number of test pieces and the variation in results will not permit conclusions to be drawn. Some of the groups contained more poor sticks than others. The abnormally high values found in A 11, A 12, and A 13 help to make comparison difficult. Evidently the data are insufficient to show whether the horizontal shearing strengths will be alike for stringers of different depths. Uniformity in selection is difficult, and it is likely that any variation in the strength found in even a long series would be masked by differences in the selection of the piece and the method of seasoning.

It must be remembered that additional depth gives additional stiffness and smaller deflections at the same fiber stress and that stiffness is an important element in bridge stringers. Even if horizontal shear controlled the strength in a given depth of stringer, greater depth may be accepted as an additional safeguard against failure at relatively low loads by reason of knots and similar defects which may have passed by unnoticed, and it will be seen that the tests include a number of stringers which failed in cross bending at unexpectedly low loads. It seems to be the case that unnoticed defects which seriously affect cross-bending tensile strength are more frequent than are the defects which give low shearing strength. If the ultimate horizontal shearing strength of timber is but little higher than the yield point in horizontal shear, as seems to be the case, it would seem reasonable to use a relatively higher working stress in shear than in fiber stress, or in other words, to make a lower factor of safety for horizontal shear than for fiber stress. This, in effect, agrees with current usage.

26. *Effect of Seasoning and of Creosoting.*—The tests may not be expected to throw light upon the effect of seasoning on the strength and stiffness of timber. The presence of knots and cross grain in a few sticks in one series, even minor variations in the quality of the wood, may easily neutralize the effect of differences in moisture. Series A and B give no marked differences in either strength or stiffness. The principal difference in results

in Series E and F is in stiffness, but the higher modulus of elasticity in the long-seasoned timber may be due in part to differences in wood. The effect of seasoning upon resistance to horizontal shear through the development of seasoning checks is important, and it is apparent that even in the earlier stages of seasoning (as shown in Series B) the formation of seasoning checks produces a marked weakening effect and must be taken into account in estimating the strength of large size timber. It may be expected that for such timber the differences in strength and stiffness of partly-seasoned timber and well-seasoned timber will be less than the differences due to variations in quality, except that the increase in seasoning checks is likely to reduce the resistance to horizontal shear.

It has been thought that the creosoting preservation process weakens timber through the action of the high temperature in the preliminary steaming process and through the presence of the oil in the walls of the cells of the wood. The opinion was once advanced that the oil had the effect of the same amount of moisture, but this seems not to have been verified. It has been shown, however, that long exposure to steam at high pressures and high temperatures is detrimental. It would seem, too, that the injection of oil will retard further seasoning and thus preclude the gain in strength which would come with time. It must be expected that differences in test pieces due to knots, cross grain, and quality of the wood may exercise a greater influence than does the process of creosoting.

It will be seen that in the shortleaf pine stringers of Series C the creosoted sticks average 22% less in elastic limit, 17% less in maximum strength, and 23% less in stiffness than do the untreated sticks. In the loblolly pine stringers of the same series, the creosoted sticks average 44% less in elastic limit, 30% less in maximum strength, and 31% less in stiffness. However, in the loblolly pine stringers of Series D the creosoted sticks show the greater strength and there is little difference in the average stiffness. The greater freedom from defects found in the creosoted stringers of Series D as compared with the defects found in the untreated stringers will account for at least a part of this seeming discrepancy.

The test pieces of Series N seem to offer good conditions for comparison. Of the pieces into which the four stringers were cut, every other piece was creosoted and the remainder were left in the natural state. The untreated test pieces had nine months longer in which to season, which probably offset any advantage which the creosoted sticks may have received in the steaming process. Two pieces in the creosoted lot had bad knots. The creosoted test beams averaged 16% lower in elastic limit, 22% lower in maximum fiber strength, and 6% lower in stiffness than did the untreated test beams. The creosoted shear blocks averaged 8% less than the untreated shear blocks.

As a whole, then, the tests go to corroborate the view that the creosoting preservative process of the ordinary practice decreases the strength and stiffness of beams; but the tests do not throw light on the cause of the difference. Attention may be called to the low resistance to compression at right angles to the grain (bearing strength) which was found in some of the creosoted loblolly stringers.

27. *Properties of the Different Woods.*—It will be noted that for the untreated stringers the range of averages for elastic limit, fiber stress, and shearing stress developed in the several woods is small if we except Series D which seems to have had a large proportion of defective sticks. Omitting Series D, the range of the averages is from 3823, 4420, and 300 lb. per sq. in. for elastic limit, fiber stress and shearing stress, respectively, in the old Douglas fir to 4336, 5430, and 354 lb. per sq. in. in the longleaf pine. The high fiber stress shown in the small test beams cut from the longleaf pine and old Douglas fir stringers is ineffective by reason of low shearing strength and the influence of defects. The low shearing strength is due largely to the presence of large seasoning checks. The longleaf pine showed the greatest effect of seasoning checks, but the shearing strength of the old Douglas fir was much lower. The loblolly pine makes a better showing than might be expected from the general softness and brashness of its wood, and this is due to a relatively high shearing strength. The loblolly pine is less stiff than the other woods. Of course, durability is not here taken into consideration. It would be interesting to know where the elastic limit in horizontal shear lies in these woods, particularly in those having large seasoning checks.

28. *General Comments.*—The ground covered by these tests is so great and the information obtained so varied that no attempt will be made to give a summary of the results. Conclusions have

been stated throughout the discussion. However, it seems proper that at the risk of repetition the following statements be given here.

1. The preponderance of failures in horizontal shear is very marked in every series of tests. The results emphasize the importance of the shearing resistance of the wood in beams of the dimensions of those tested. The cross-breaking failures were in sticks having bad knots and cross grain. A few of these defective sticks would not be called merchantable timber, but many of them might pass inspection as it is usually made. The influence of defects is very marked. Knots, cross grain, and seasoning checks act to give low strength. Any tendency to relax requirements and inspection should be avoided, unless accompanied with the use of lower working stresses.

2. The horizontal shearing resistance developed in the stringers is low in every series of tests. The averages range from 300 to 390 lb. per sq. in., and in individual cases the stress is as low as 200 lb. per sq. in. Comparatively little difference in shearing resistance is found for the different kinds and conditions of wood, for in the clear sticks of the stronger woods large seasoning checks act to prevent the utilization of the full cross-breaking strength of the timber.

3. For the cross-breaking failures the fiber stress developed was also generally low, averaging for the untreated timber from 3690 lb. per sq. in. in the old Douglas fir to 5300 lb. per sq. in. in the longleaf pine. One longleaf pine stringer developed a fiber stress of 8410 lb. per sq. in., and a value as low as 2530 lb. per sq. in. was found.

4. The elastic limit of the beams is seriously affected by defects like knots and cross grain. However, in general, the fiber stress at the elastic limit is proportionally high, the ratio to the fiber stress at failure averaging from 0.67 to 0.90 for the several series of tests.

5. The strength developed in the small test beams cut from the top and bottom of the stringers averages from 50% to 100% higher than that obtained in the stringers, and the results show the futility of taking tests of small sticks as a criterion of the strength of full-size structural timber. The shearing strength developed in the stringers was 60% to 100% of the shearing strength developed in shear blocks cut from the uninjured end of

the stringers at mid-depth and having their full thickness; but these strengths of the shear blocks are much less than will be obtained on small pieces of selected timber.

6. In woods which develop large checks and cracks in seasoning, care should be given to avoid rapid and uneven seasoning in large sticks. Seasoning checks should be recognized as a common source of weakness.

7. The tests of creosoted sticks are insufficient to warrant drawing conclusions. They seem to corroborate the view that timber treated by the creosoting process as usually operated has somewhat less strength and stiffness than untreated timber. The stopping of further seasoning in the creosoted wood is an element which should be considered in such a comparison.

8. The fact that sticks having knots and cross grain are generally less stiff than clear sticks results in the weaker stick taking less than its share of load and the stronger and stiffer stick taking more than its share when defective and clear sticks are placed side by side and are loaded so as to have the same deflection. It is evident that stringers having defects may not receive their calculated proportion of the load. It is interesting to note that the modulus of elasticity calculated from deflections is less than the values derived from the observed deformations of the outer fibers.

9. It is evident that the defects found in structural timber have a strong influence on strength and that rigid inspection should be given.

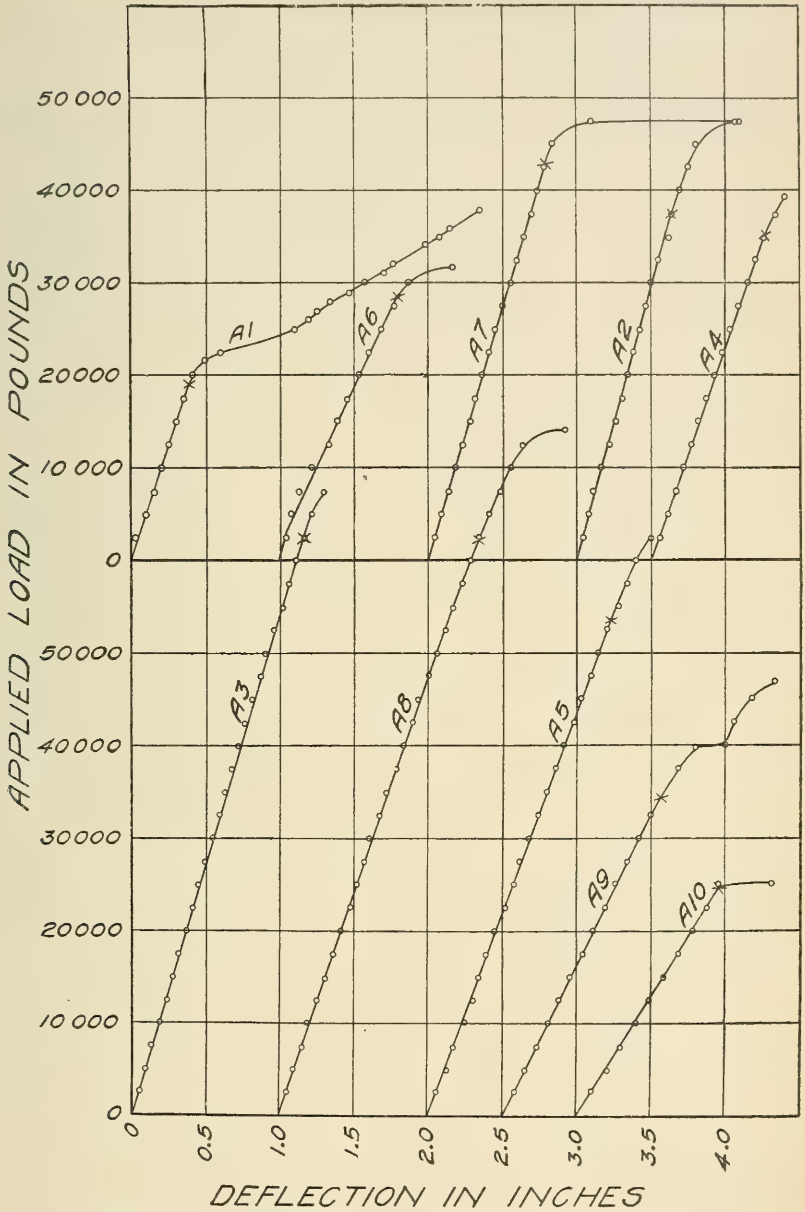

FIG. 11. LOAD-DEFLECTION DIAGRAMS FOR LARGE BEAMS.

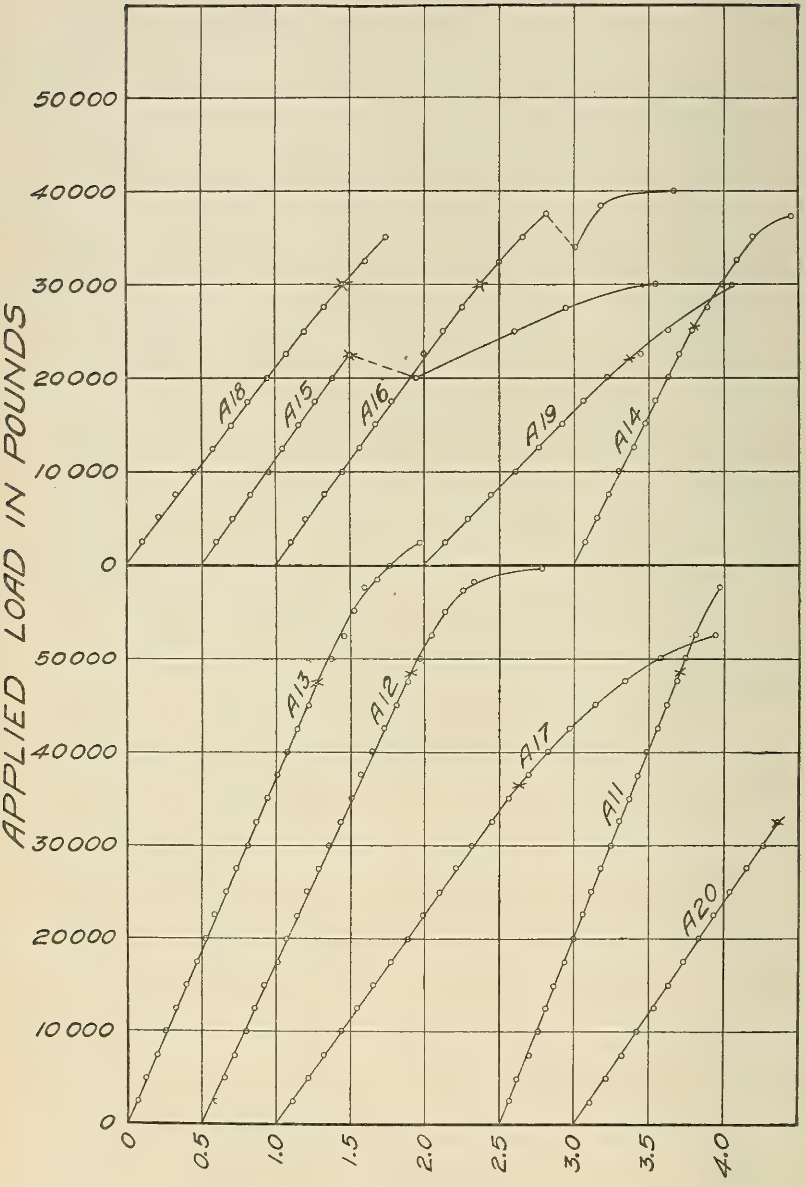

FIG. 12. LOAD-DEFLECTION DIAGRAMS FOR LARGE BEAMS.

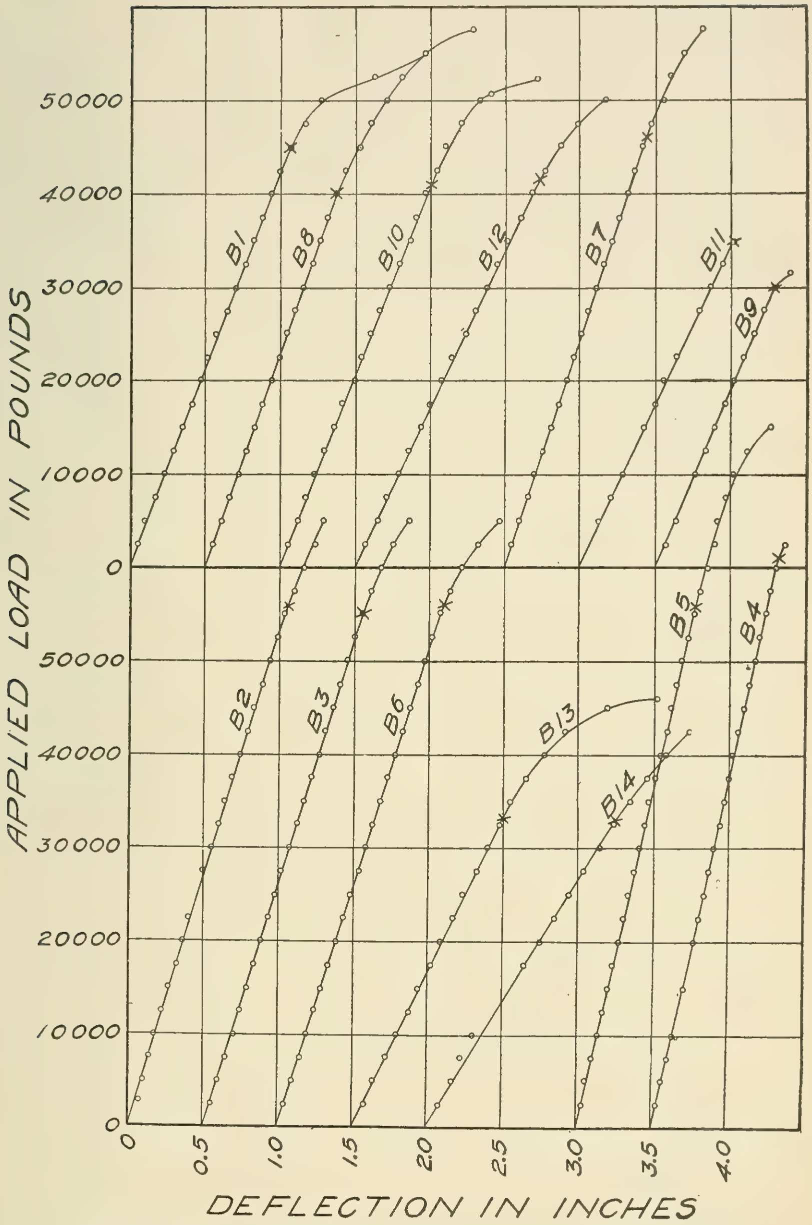

FIG. 13. LOAD-DEFLECTION DIAGRAMS FOR LARGE BEAMS.

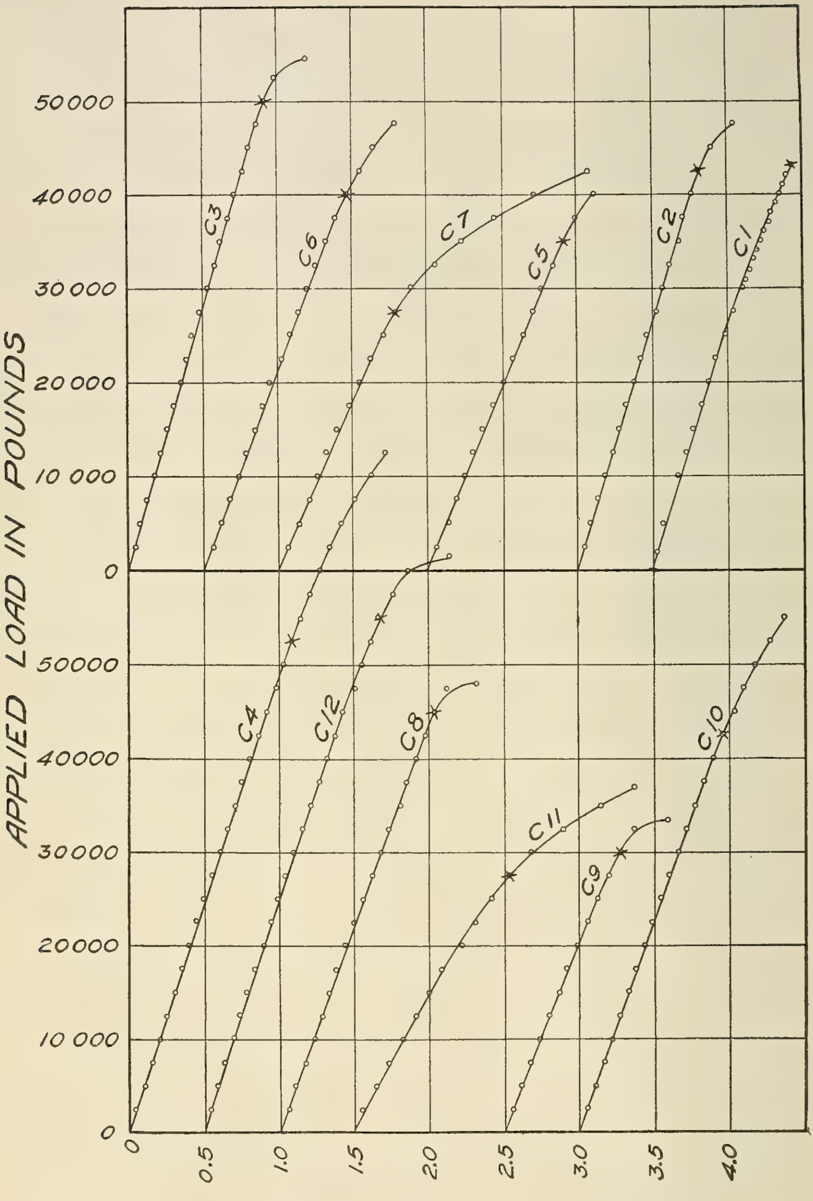

FIG. 14. LOAD-DEFLECTION DIAGRAMS FOR LARGE BEAMS.

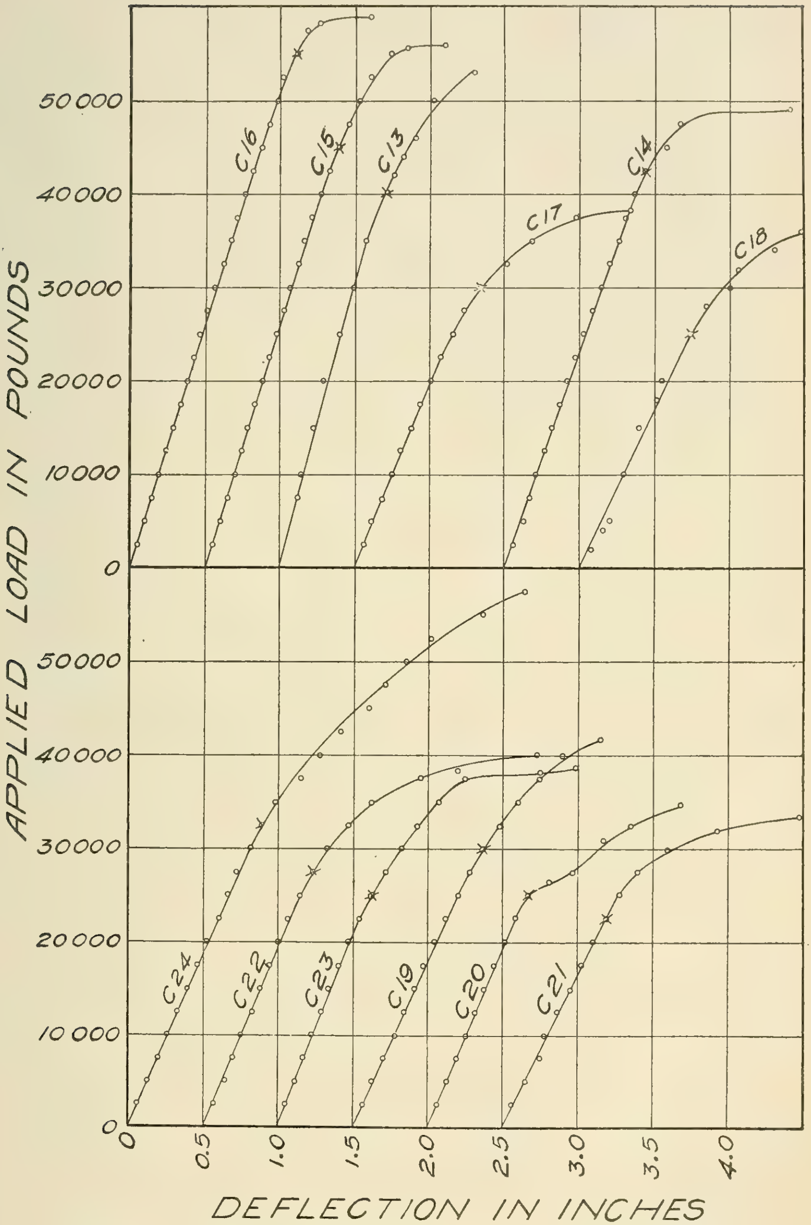

FIG. 15. LOAD-DEFLECTION DIAGRAMS FOR LARGE BEAMS.

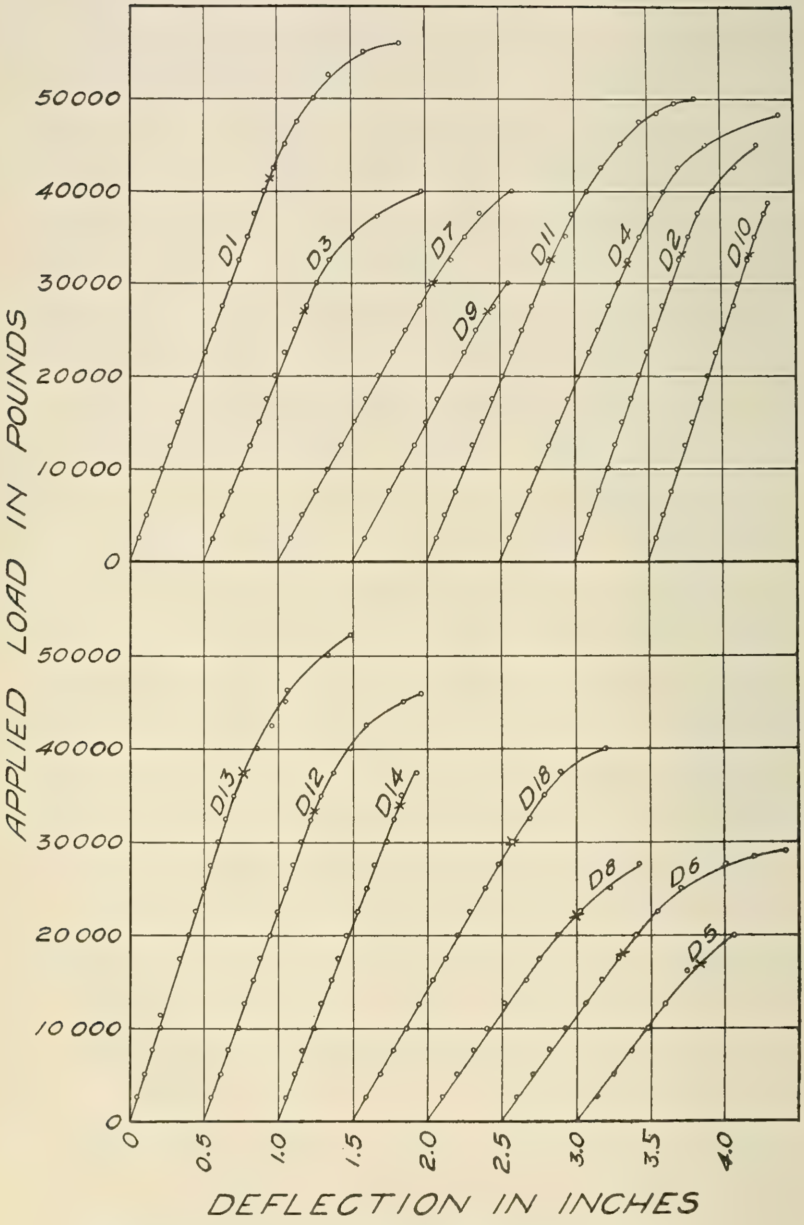

FIG. 16. LOAD-DEFLECTION DIAGRAMS FOR LARGE BEAMS.

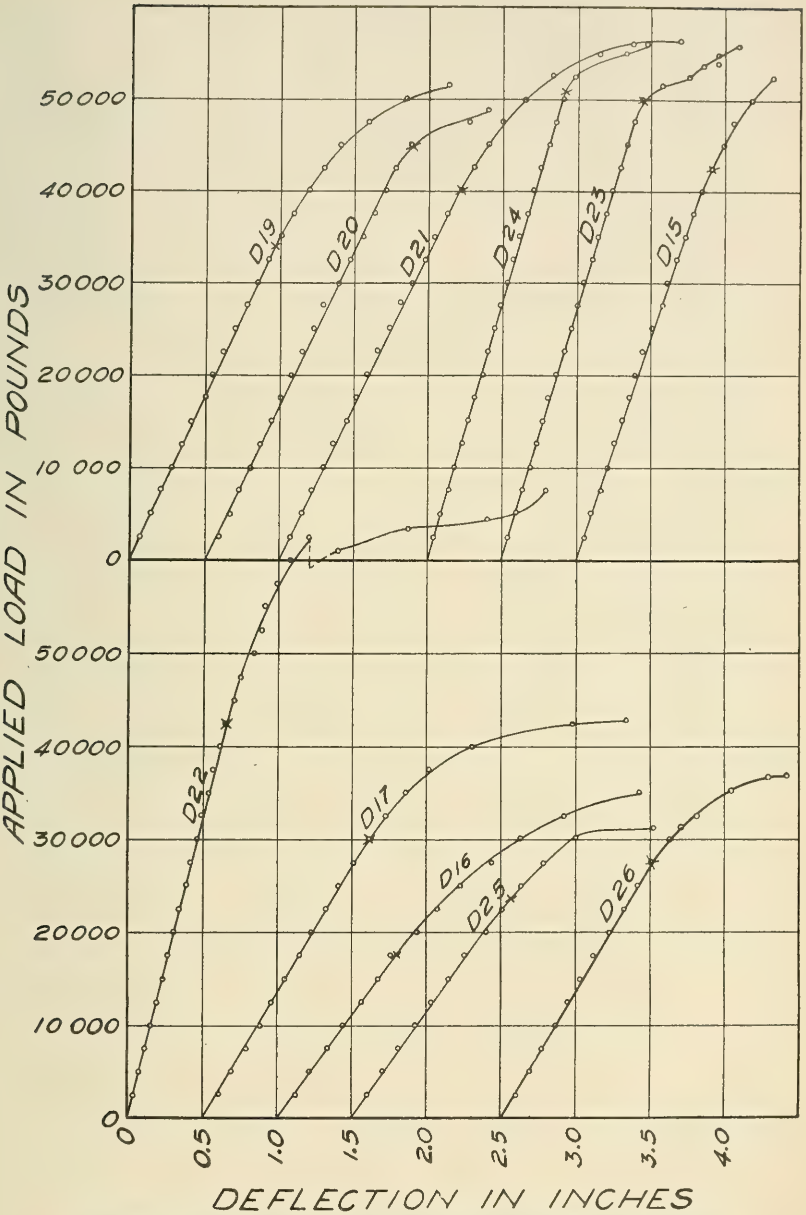

FIG. 17. LOAD-DEFLECTION DIAGRAMS FOR LARGE BEAMS.

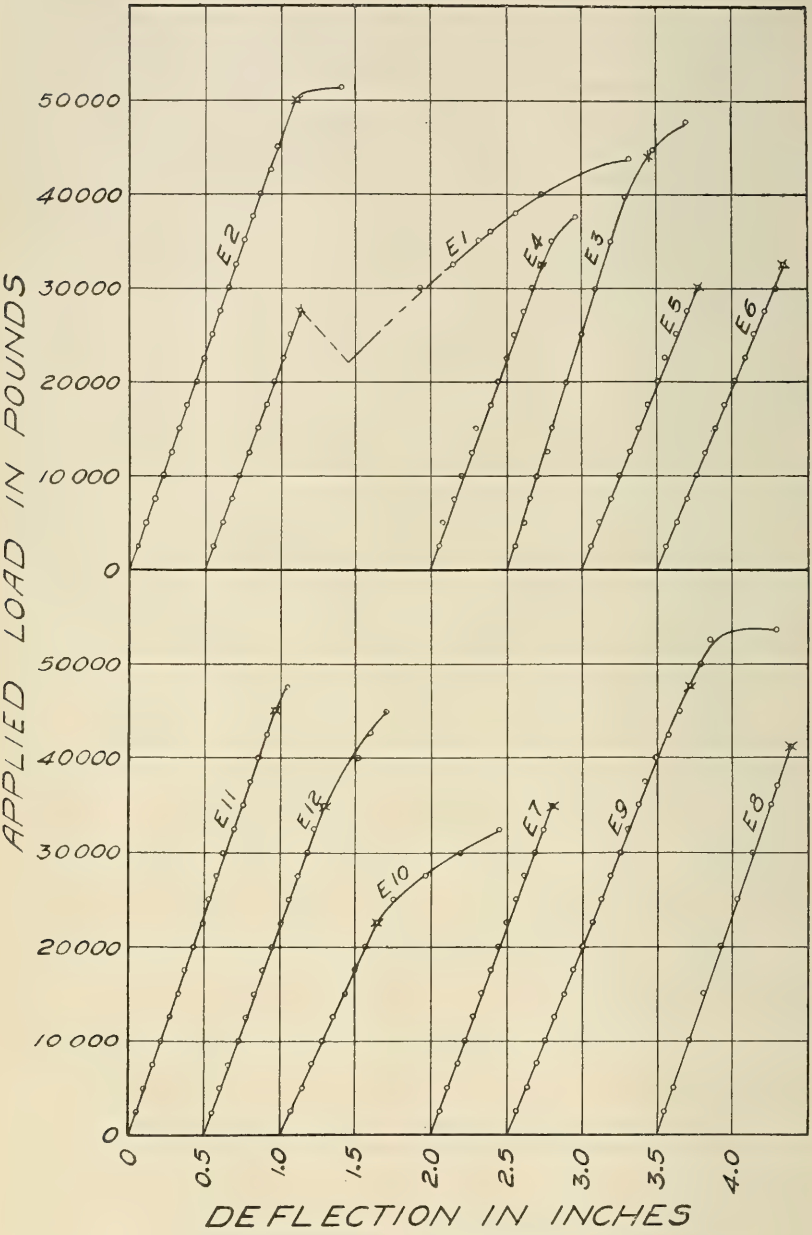

FIG. 18. LOAD-DEFLECTION DIAGRAMS FOR LARGE BEAMS.

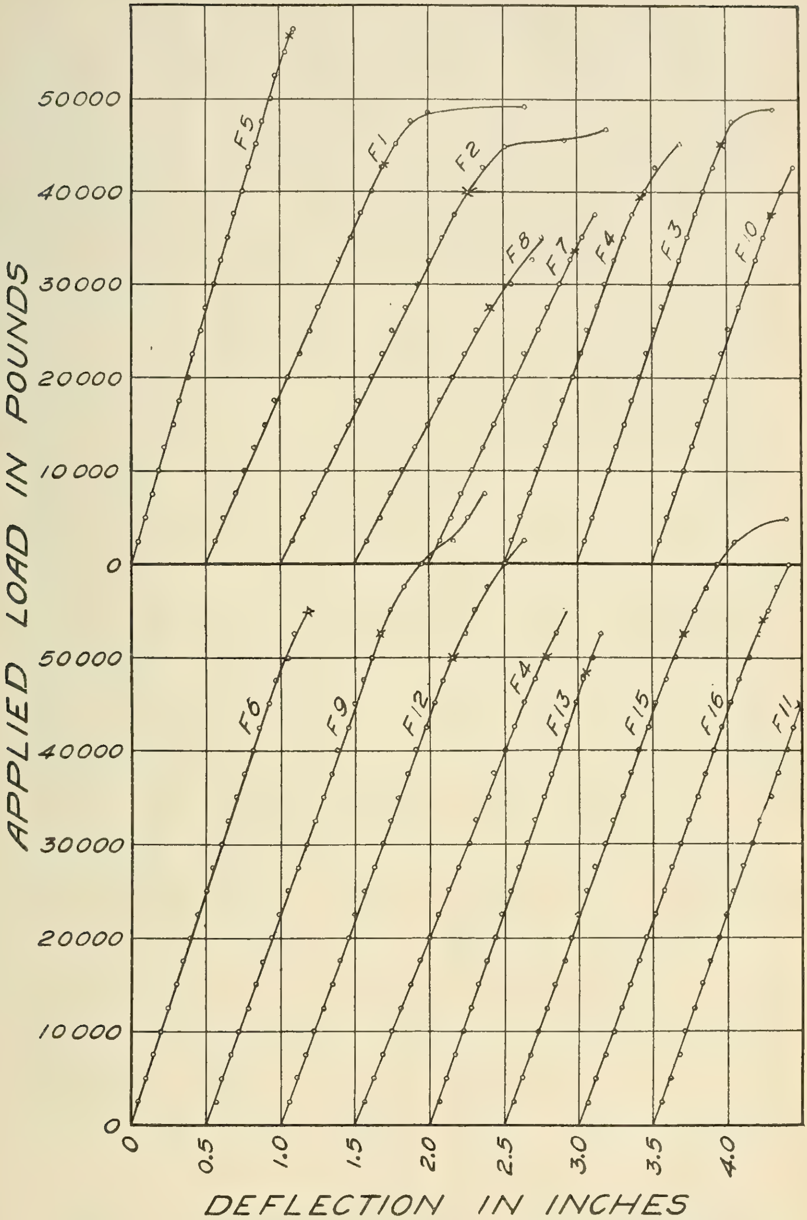

FIG. 19. LOAD-DEFLECTION DIAGRAMS FOR LARGE BEAMS.

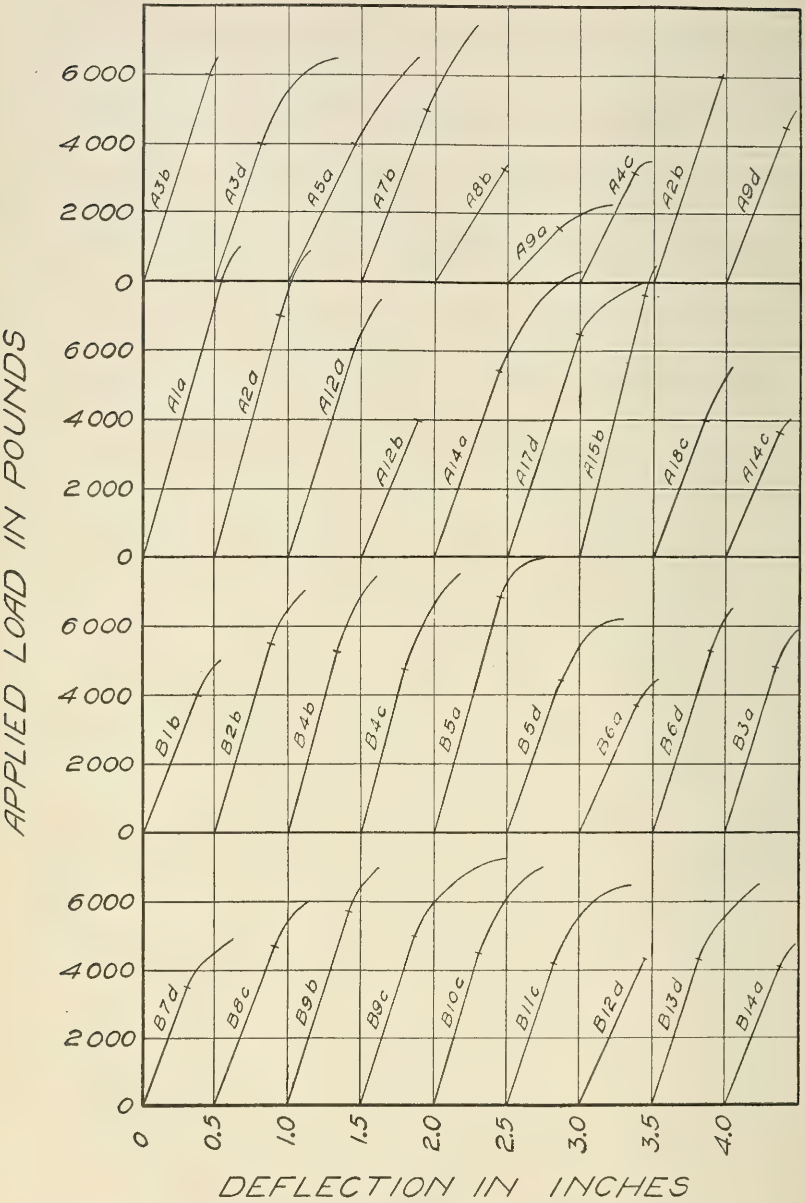

FIG 20. LOAD-DEFLECTION DIAGRAMS FOR SMALL TEST BEAMS.

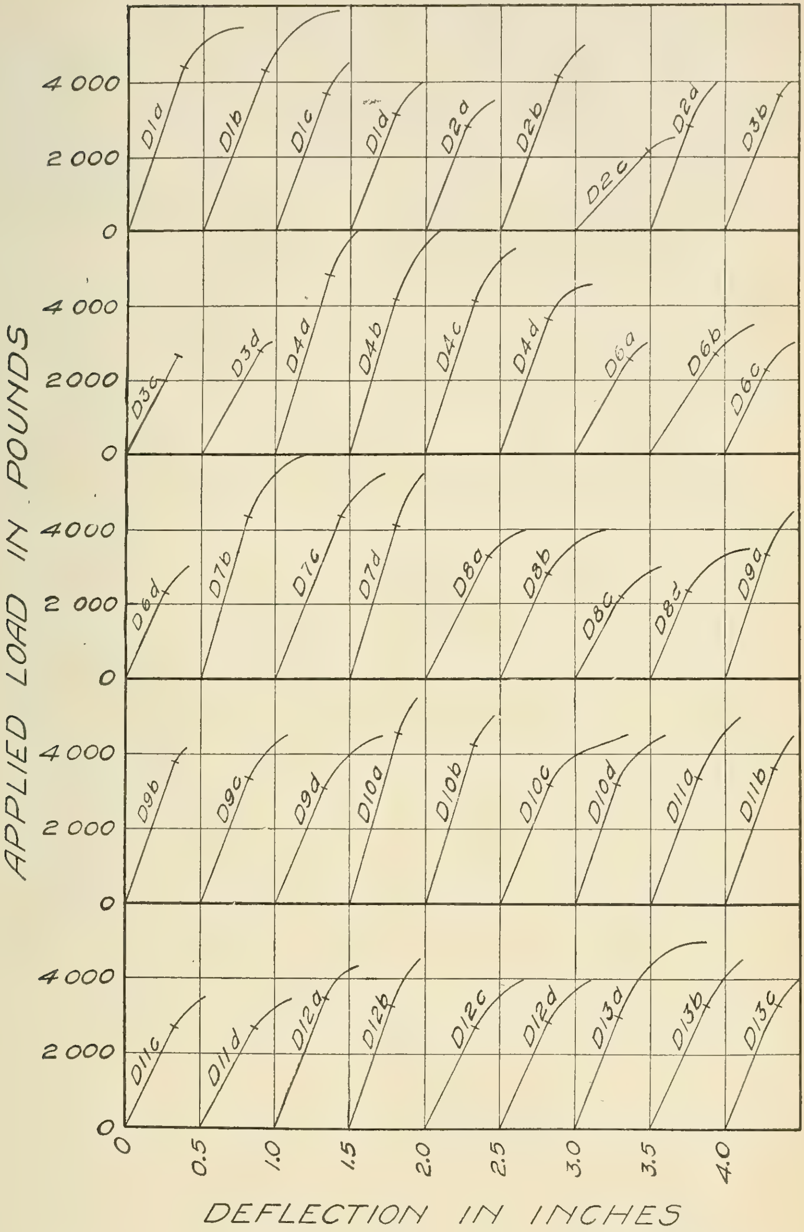

FIG. 21. LOAD-DEFLECTION DIAGRAMS FOR SMALL TEST BEAMS.

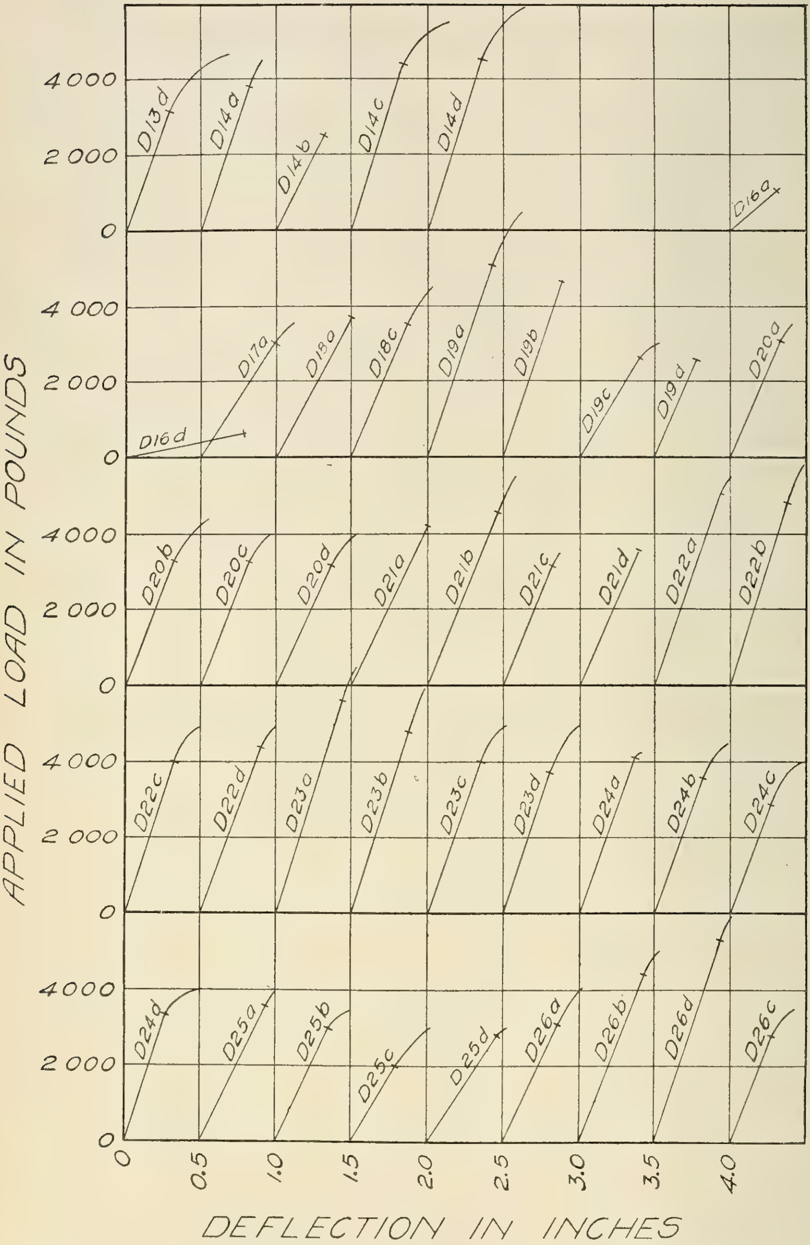

FIG. 22. LOAD-DEFLECTION DIAGRAMS FOR SMALL TEST BEAMS.

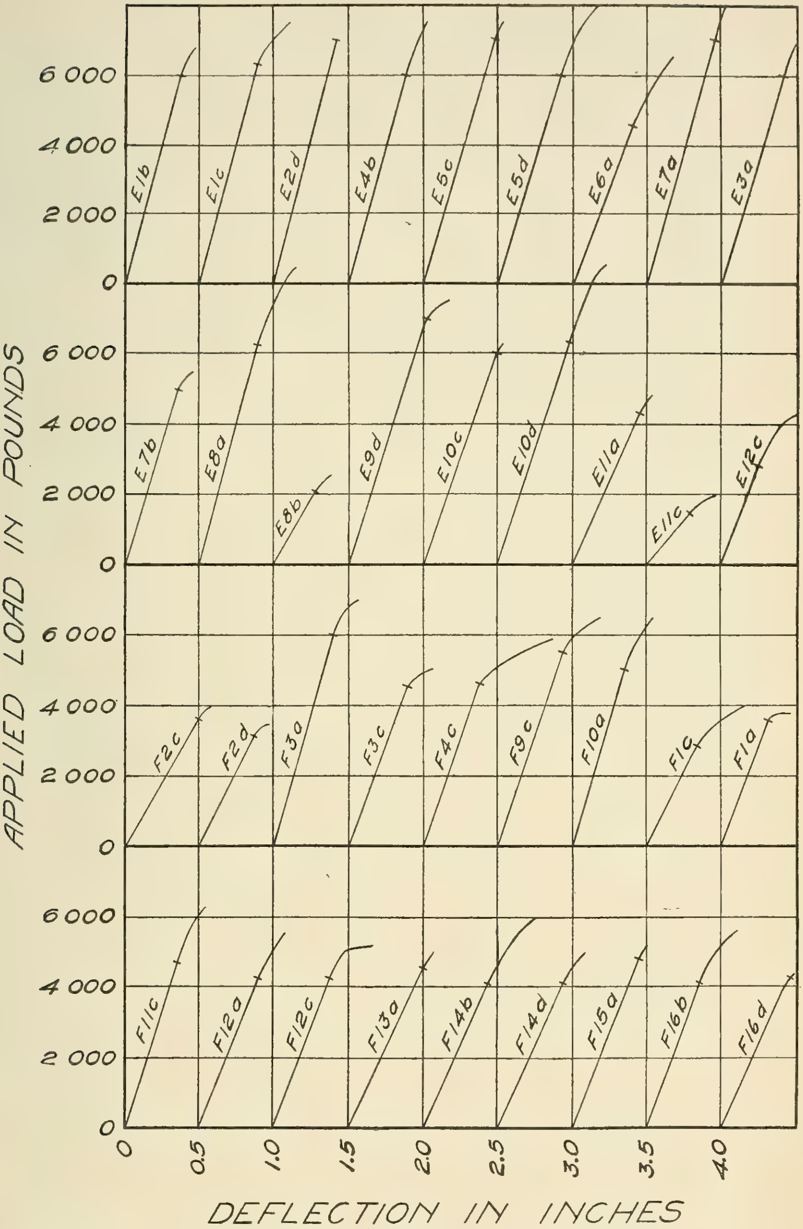

FIG. 23. LOAD-DEFLECTION DIAGRAMS FOR SMALL TEST BEAMS.

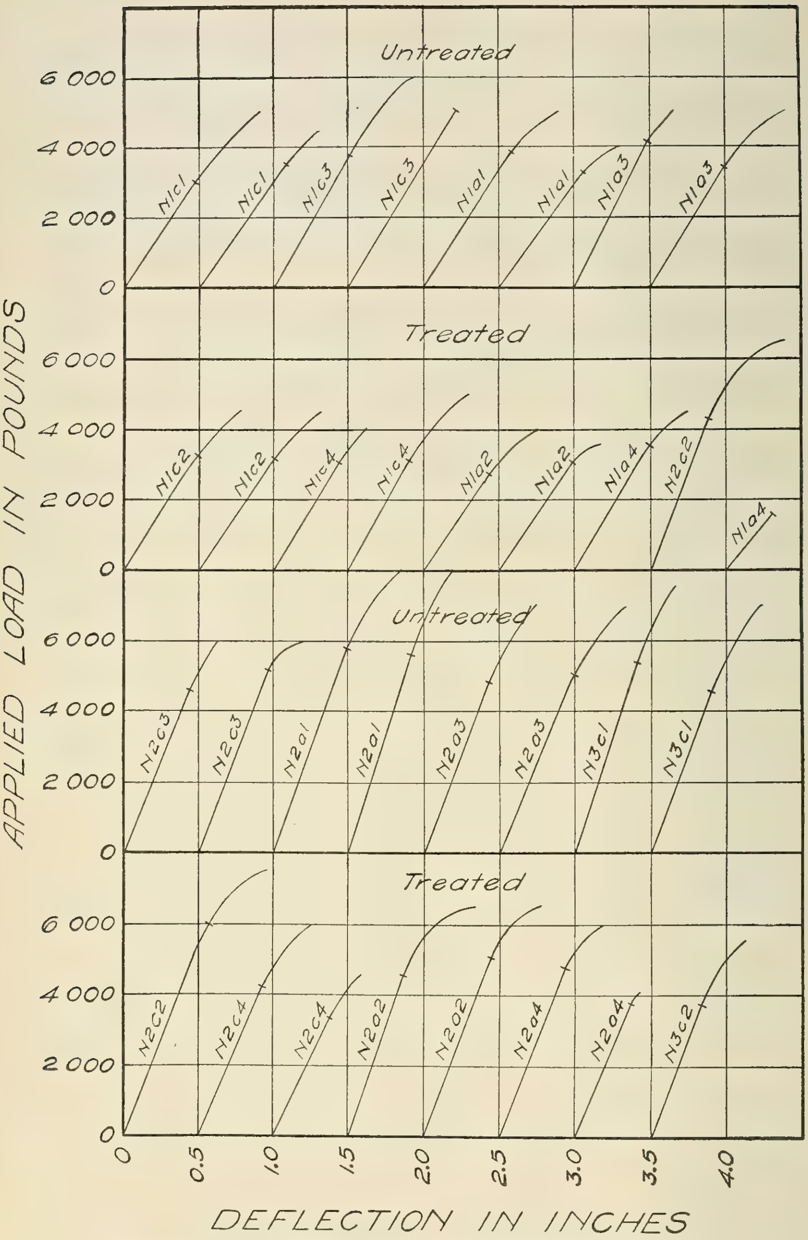

FIG. 24. LOAD-DEFLECTION DIAGRAMS FOR SERIES N.

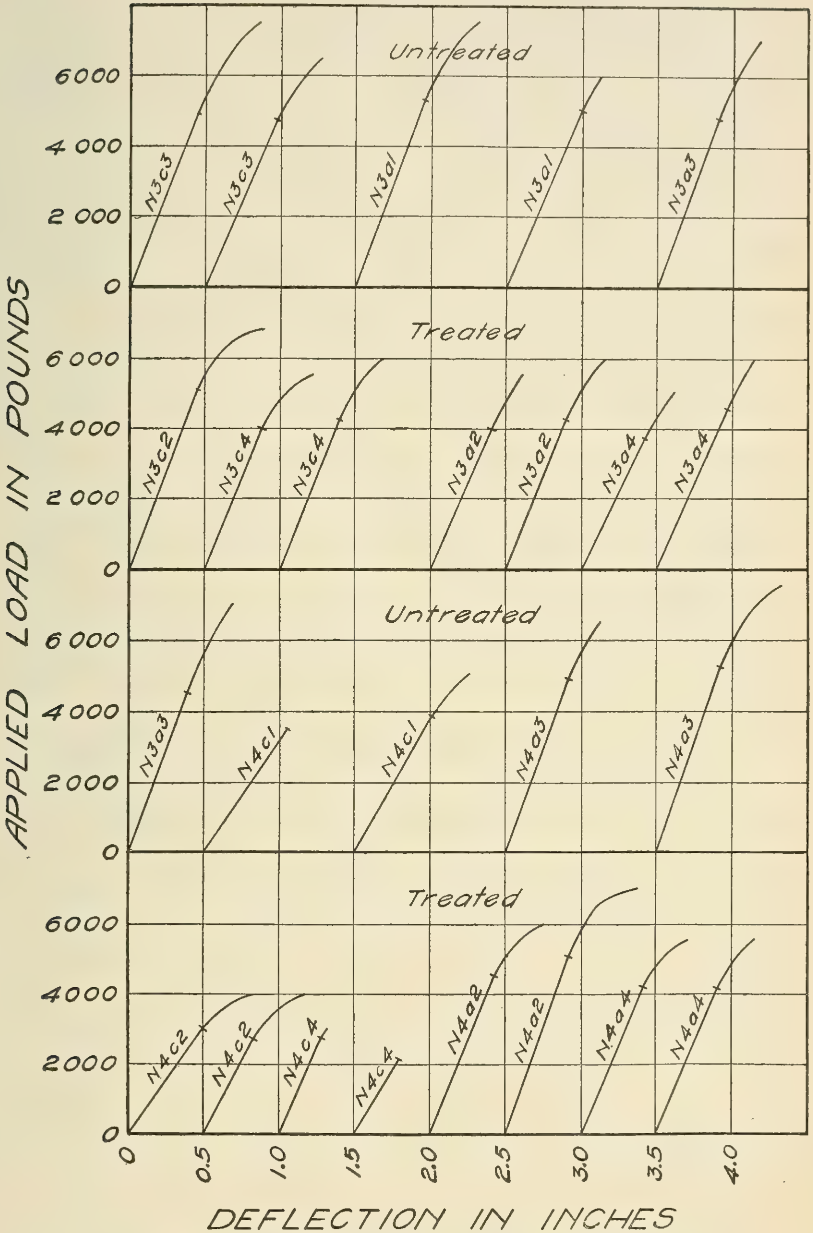

FIG. 25. LOAD-DEFLECTION DIAGRAMS FOR SERIES N.

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BULLETIN NO. 42

THE EFFECT OF KEYWAYS ON THE STRENGTH OF SHAFTS

BY

HERBERT F. MOORE

UNIVERSITY OF ILLINOIS
ENGINEERING EXPERIMENT STATION

URBANA, ILLINOIS
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UNIVERSITY OF ILLINOIS
ENGINEERING EXPERIMENT STATION

BULLETIN NO. 42 DECEMBER 1909

THE EFFECT OF KEYWAYS ON THE STRENGTH OF SHAFTS

BY HERBERT F. MOORE, ASSISTANT PROFESSOR OF THEORETICAL AND APPLIED MECHANICS, ENGINEERING EXPERIMENT STATION

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THE EFFECT OF KEYWAYS ON THE STRENGTH OF SHAFTS.

I. INTRODUCTION.

1. *Preliminary.*—In the transmission of power by means of shafting and pulleys or gears, the common method of fastening the pulley or gear to the shaft, so that the two will rotate together, is by means of a key inserted in a keyway cut in the shaft, and extending into a corresponding keyway cut in the hub of the pulley or gear. The strength and the proper proportioning of keys have been subjects of considerable study and of some experimentation, but the effect of the keyway on the torsional strength of the shaft has apparently been studied but little. Evidently, the keyway must weaken the shaft in which it is cut. It would seem that the sharp corners of the keyway and its location at one side of the shaft might weaken the shaft more than the relatively small size of the keyway would lead us to expect. In view of the very extensive use of shafts with keyways and the small amount of information available on the subject, the effect of keyways on the torsional strength of shafts has seemed to the writer a problem worthy of some experimental study. This bulletin is an account of a brief investigation carried on in the Laboratory of Applied Mechanics by the Engineering Experiment Station of the University of Illinois.

The mathematical analysis of the strength of a shaft with a keyway cut in it is a problem of great complexity. The common theory of stresses in shafts applies only to shafts of circular cross-section. Mathematical researches by Saint Venant and others have developed the theory of square, rectangular, triangular, and elliptical shafts, but, so far as the writer knows, there has been no successful attempt to develop the mathematical theory of the stress in a shaft with a keyway cut in it. However, as the range of sizes of shafts and keys in common use is not very great, it was thought that an experimental study of the effect of keyways on the strength of shafts might lead to formulas which may be safely used in nearly all the cases met by the designer of shafts and keys.

It was found possible to investigate by direct experiment the effect of keyways on the strength of shafts of various sizes, and to study the effect of keyways on the strength of shafts subjected to combined bending and twisting.

For this use in calculation and design, it was thought best to coin a term to permit comparison between a shaft with keyway and an uncut shaft. Adopting a nomenclature similar to that used by many writers on the strength of riveted joints, the ratio of the strength of a shaft with a keyway to the strength of a similar shaft without a keyway is hereafter spoken of as the *efficiency* of the shaft with keyway.

If a shaft with a pulley keyed to it is given a permanent twist, the removal of the pulley is frequently a matter of great difficulty; while if a shaft carries a sleeve or gear with a key sliding in a keyway, any permanent twist practically ruins the shaft. For these reasons the elastic limit of a shaft under torsion is taken as the measure of its strength.

2. *Acknowledgment.*—A considerable part of the experimental work herein described was performed by the following senior students of the College of Engineering of the University of Illinois in the preparation of their graduating theses in Mechanical Engineering:

Mr. F. E. Leidendeker, Class of 1908.
Mr. O. Craig and Mr. J. C. Lund, Class of 1909.

The writer wishes to express his appreciation of the faithful and careful work of the above students. Acknowledgment is also made to the Whitney Manufacturing Company of Hartford, Connecticut, for cutters for keyways of the Woodruff system of keys.

The work was undertaken with the approval of Professor Arthur N. Talbot, head of the department of Theoretical and Applied Mechanics, to whom the writer is indebted for many helpful suggestions, both as to methods of experimentation and to interpretation and arrangement of results.

3. *Notation and Formulas.*—The following notation is used:

d = actual diameter of shaft in inches.
w = width of keyway ÷ diameter of shaft.
h = depth of keyway ÷ diameter of shaft.
T = torsional (twisting) moment on shaft in inch-pounds.
M = bending moment on shaft in inch-pounds.

J = polar moment of inertia of cross-section of shaft (for circular shaft, $J = \frac{d^4}{10.2}$).

f = greatest fiber stress in shaft due to torsion.

Θ = angle of twist of shaft in degrees.

l = length of shaft in inches.

E_s = modulus of elasticity of material of shaft in shear (torsion).

e = efficiency of shaft with keyway.

k = ratio of angle of twist of shaft with keyway to angle of twist of similar uncut shaft.

$H. P.$ = horse-power.

$r. p. m.$ = number of revolutions per minute.

The following formulas are used:

$$T = \frac{2fJ}{d}$$

$$\Theta = \frac{2fl}{E_s d} \times 57.3$$

$$T = 63\,020 \frac{H.P.}{r.p.m.}$$

The first two formulas are based on the following assumptions; (1) that a plane section of the shaft remains plane during torsion; and (2) that the fiber stress varies uniformly from zero at the axis of the shaft to a maximum at the outer fiber, i. e., the modulus of elasticity for shear remains constant. The first assumption is not true for shafts which are not circular in cross-section.

II. TEST PIECES, TESTS, AND METHOD OF TESTING.

4. *Test Pieces.*—The principal object of this investigation was to obtain values of the efficiency of shafts with keyways, and as nearly all shafting in common use is cold-rolled, the principal series of tests was made on specimens of cold-rolled steel shafting. The diameters of the test shafts of these series were $1\frac{1}{4}$, $1\frac{9}{16}$, $1\frac{15}{16}$, and $2\frac{1}{4}$ in. Shafts were tested under simple torsion and under torsion combined with bending. The bending moment applied to the shaft was in one case equal to the torsional moment, and in another equal to three-fifths the torsional moment. Table 1 shows the sizes of shafts and the sizes of the keyways cut in them.

TABLE 1.

DIMENSIONS OF SHAFTS AND KEYWAYS.
SERIES OF 1909.

Dia. Shaft inches d	Relative Dimensions of Keyway		Actual Dimensions of Keyway inches	
	w	h	width	depth
1¼	0.25	0.125	$\frac{5}{16}$	0.156
	0.50	0.125	⅝	0.156
	0.25	0.1875	$\frac{5}{16}$	0.234
$1\frac{9}{16}$	0.25	0.125	$\frac{25}{64}$	0.195
	0.50	0.125	$\frac{25}{32}$	0.195
	0.25	0.1875	$\frac{25}{64}$	0.293
$1\frac{15}{16}$	0.25	0.125	$\frac{31}{64}$	0.242
	0.50	0.125	$\frac{31}{32}$	0.242
	0.25	0.1875	$\frac{31}{64}$	0.363
2¼	0.25	0.125	$\frac{9}{16}$	0.281
	0.50	0.125	1⅛	0.281
	0.25	0.1875	$\frac{9}{16}$	0.422

For transmitting power, it is common American practice to use a square key whose width and depth are each equal to about one-fourth the diameter of the shaft (Kent's Pocket-Book, pp. 975 - 976). This means a keyway in the shaft in which $w = 0.25$ and $h = 0.125$. The depth of keyway is measured as shown in Fig. 1.

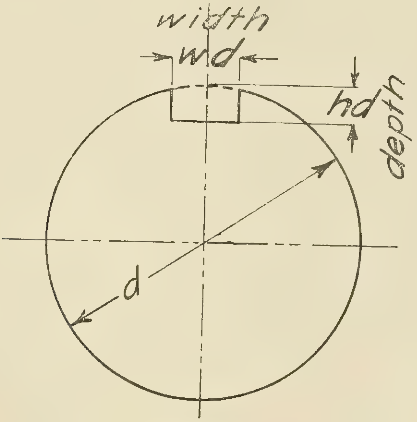

FIG. 1.

Shafts were also tested with keyways for the Woodruff system of keying. The outline of the Woodruff key and its keyway are shown in Fig. 2. In choosing the sizes of Woodruff keyways to be cut in the test shafts, the shearing strengths of various standard sizes of keys were figured, and a standard size was chosen such that the shearing strength of two keys equaled, as nearly as possible, the torsional strength of the solid test shaft in question. The sizes of the Woodruff keys chosen are shown in Tables 2 and 4.

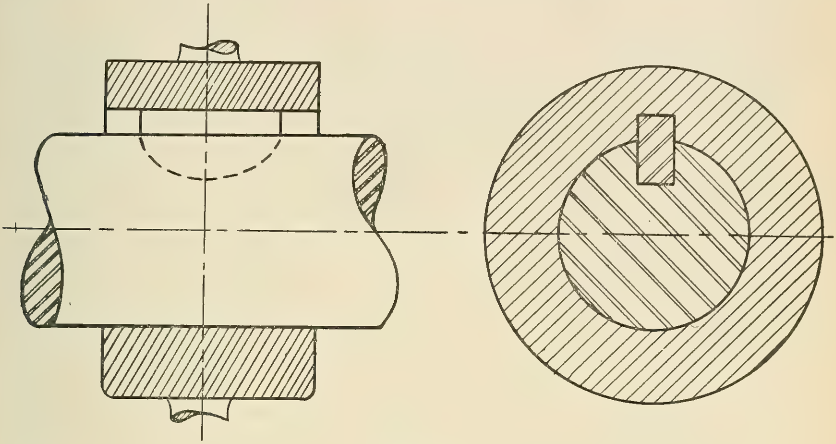

FIG. 2.

In addition to the above tests for effect of single keyways on the strength of cold-rolled shafting, tests were made (principally in the 1908 series) which yielded data on the following subjects: ultimate strength of shafts with keyways; effect of two keyways at right angles; effect of length of keyway; effect of keyways on turned steel shafting.

All keyways, except in the tests for studying the effect of length of keyways, were cut to a length equal to about four times the diameter of the shaft, no keyway being longer than eight inches.

All material for the test shafts was bought in the open market. Both the cold-rolled and the turned shafting were of ordinary soft steel. All tests were planned in duplicate, and with a very few exceptions, all tests were made in duplicate.

5. *Description of Apparatus.*—All shafts tested under simple twisting were tested in the 230 000 in.-lb. Olsen torsion testing machine in the Laboratory of Applied Mechanics of the Univer-

sity of Illinois. To the test shaft were attached long arms in pairs, one arm of a pair carrying a pointer, and the other a scale. The angle of twist between these two arms was measured by the motion of the pointer over the scale. Fig. 3 shows a test shaft of the 1909 series in position with the pointers and scales attached. In this shaft were cut four keyways, each keyway being 90° round the shaft from the adjacent keyways. The angle of twist of the shaft was measured over five portions of its length, four portions of length being occupied by the keyways and one being without keyway. The latter portion was generally at the middle of the shaft.

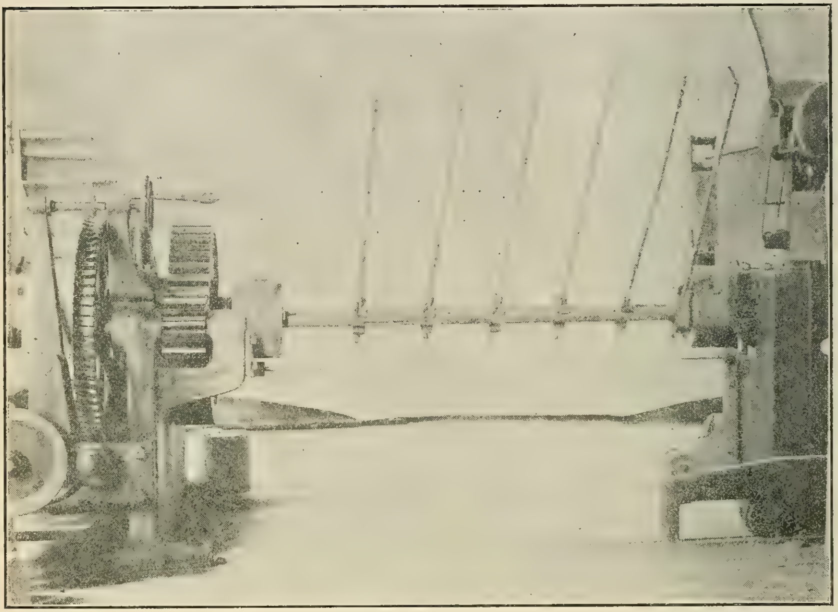

FIG. 3.

The apparatus used for studying the effect of combined twisting and bending on shafts with keyways is shown in Fig. 4. To the ends of the test shaft S were keyed arms AA extending at right angles to the shaft. Equal forces *FF* were applied in a vertical direction at points on these arms at a distance p from the axis of the shaft. The test shaft was supported on bearings GG by means of steel balls B, bearing on hardened steel bushings.

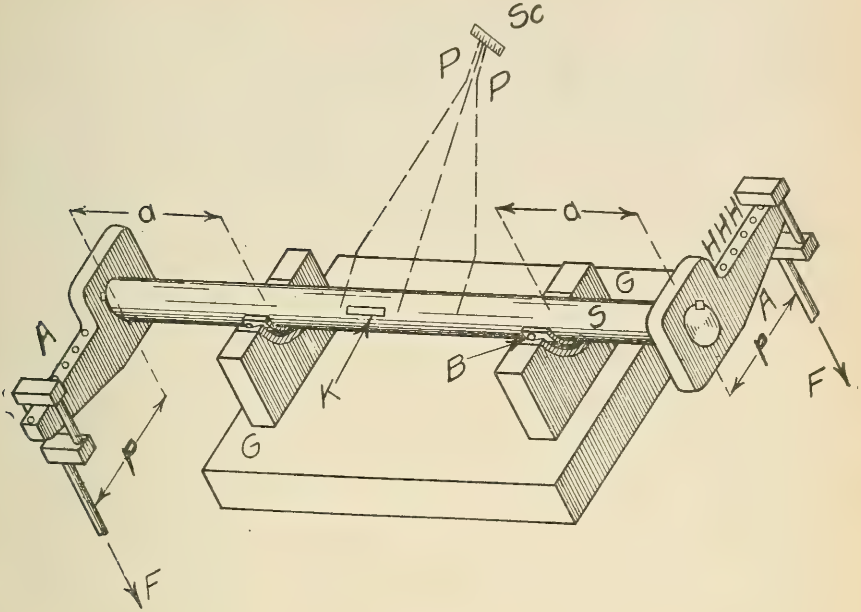

FIG. 4.

The distance a from the arm A to the center of the nearer bearing was the same at the two ends. The test shaft then was subjected to a bending moment Fa over that portion between bearings, and to a twisting moment Fp over its entire length (the very small friction of the ball bearings being neglected). The ratio of the twisting moment to the bending moment equals $\frac{p}{a}$.

The forces FF were applied by the moving crosshead of a testing machine. The entire apparatus shown in Fig. 4 rested on the upper weighing head of the testing machine. The load registered on the weighing table of the machine was equal to $2F$. The force F was transmitted to each of the arms AA through a small spherical pointed knob resting in one of the holes HHHH, the twisting arm being varied by using different holes. The bearings GG could be moved axially along the shaft, thus allowing the bending moment to be varied. In the tests under combined twisting and bending, the keyway cut in the test shaft was located at one side of the center of the shaft, and the angle of twist was measured over the portion of the shaft containing the keyway, and also over the solid portion. The apparatus for measuring angle of twist was the same as in the tests under simple torsion, and is shown in the diagram in Fig. 4, in which K represents the keyway, PP the pointers, and Sc the scale.

6. *Procedure of Tests.*—In the 1908 tests, which were all on shafts under twisting only, the method of conducting the test was to apply torsion continuously until the yield point was passed, frequent readings of twisting moment and of corresponding angle of twist being taken. After the yield point was passed, the twist-measuring apparatus was removed, and the torsion applied until the shaft broke, the maximum twisting moment carried being noted.

In the 1909 tests, both under simple torsion and under combined twisting and bending, the method of procedure was as follows: A small initial load was applied to the shaft, and an initial reading taken on the twist-measuring apparatus; more load was then applied and the angle of twist read; the load was then released to its initial value, and the angle of twist again read, any permanent set being thus detected; a load slightly greater than the previously applied load was then put on the shaft, and this load in turn released to the initial value. This process was repeated with applications of increasing loads until the yield point of the shaft was passed.

III. DATA AND RESULTS.

7. *Ultimate Strength of Shafts with and without Keyways.*—Table 2 (tests of 1908) shows the results of tests to breaking of shafts with and without keyways. It seems that a shaft with a single keyway of common dimensions has about the same ultimate strength as a shaft without keyway. In the torsional tests to destruction, after the elastic limit of the shaft had been passed, the keyways gradually closed up and at rupture they were entirely closed. The larger keyways and the two keyways 90° apart lowered the ultimate strength somewhat. The variation in strength due to difference in material of the shafting seems to cause more variation in ultimate strength than is caused by different keyways. As previously pointed out, the elastic limit of a shaft is more significant than its ultimate strength.

TABLE 2.

ULTIMATE STRENGTH OF SHAFTS WITH KEYWAYS AND WITHOUT KEYWAYS.

Values are the average results of two tests.

Diameter of Shaft inches	Keyway		Maximum Twisting Moment in.—lb.	Maximum Computed Fiber Stress (solid shaft) lb. per sq. in.	H. P. 100 r.p.m.	Remarks
	Width inches	Depth inches				
1¼ in. cold-rolled	0	0	27 400	70 550	43.4	Shaft without keyway
	¼	¼	27 600	71 000	43.8	
	⅜	¼	30 300	78 000	48.0	
	¼	⅜	24 400	63 000	38.7	
	¼	⅛	27 600	71 000	43.8	
	⅜	⅛	27 200	70 000	43.1	
	No. 10	No. 10	25 500	65 800	40.4	Keyway for No. 10 Woodruff
	No. 15	No. 15	26 200	67 600	41.6	Keyway for No. 15 Woodruff
	¼	¼	25 300	65 200	40.1	2 keyways 90° apart
1¼ in. turned	0	0	25 300	65 200	40.1	Shaft without keyway
	¼	¼	25 800	66 400	40.9	
	¼	⅜	25 500	65 700	40.4	
	No. 10	No. 10	23 700	61 000	37.6	Keyway for No. 10 Woodruff
	No. 15	No. 15	24 100	62 100	38.2	Keyway for No. 15 Woodruff
1⅝ in. cold-rolled	0	0	54 700	65 000	86.8	Shaft without keyway
	11/32	11/64	56 400	67 000	89.6	
2 in. cold-rolled	0	0	103 700	66 000	164.5	Shaft without keyway
	7/16	7/32	102 100	65 000	162.0	
	7/16	7/16	101 500	64 600	161.1	
	7/16	9/16	94 200	60 000	149.1	
	9/16	7/32	104 500	66 500	165.7	
	No. 16	No. 16	105 300	67 000	167.0	Keyway for No. 16 Woodruff
	No. 21	No. 21	100 500	64 000	158.7	Keyway for No. 21 Woodruff
2 in. turned	0	0	100 500	64 000	158.7	Shaft without keyway
	7/16	7/32	94 200	60 000	149.1	
	9/16	7/32	94 200	60 000	149.1	
	No. 16	No. 16	89 800	57 200	142.5	Keyway for No. 16 Woodruff
	No. 21	No. 21	85 000	54 100	134.8	Keyway for No. 21 Woodruff

8. *Effect of Length of Keyway.*—Several special tests were made on the effect of keyways on the strength of shafts. In general, these tests, while too few in number to justify final conclusions, gave suggestive or tentative results.

The keyways in nearly all the shafts tested were cut to a total length of about four times the diameter of the shaft, no keyway being longer than 8 inches; but in several special shafts, keyways were cut 18 inches long. No difference between *strength* of shafts with long keyways and of similar shafts with the usual shorter keyways was observed.

9. *Effect of Two Keyways 90° Apart.*—One test was made of a shaft having cut in it two keyways 90° apart, the two keyways

being located in the same cross-section of the shaft. While the result of this single test is by no means conclusive, it is of interest to note that the reduction in strength at elastic limit of the shaft by these two keyways was nearly three times as great as the reduction in strength at elastic limit of a similar shaft by one such keyway.

10. *Effect of Keyways on Turned Shafting.*—The tests made were mainly on cold-rolled shafting, but in the 1908 series a few tests were made on test specimens of turned shafting. Owing to the imperfect method used in the 1908 tests for locating the elastic limit, these results must be regarded as tentative. In these tests the effect of keyways on the strength of turned shafting at the elastic limit seemed to be about the same as the effect of keyways on the strength of cold-rolled shafting.

11. *Strengthening Effect of Key in Place.*—During the tests, the question arose as to the difference in strength of a shaft with empty keyway and a shaft on which a pulley was keyed in place, the key nearly filling the keyway. It was judged best, however, to test shafts with empty keyways, as there is usually a part of the keyway at either end not filled by the key, and a perfect fit of the key in the keyway is by no means certain, especially after long service and, therefore, for purposes of design the empty keyway determines the strength of the shaft.

TABLE 3.

RATIO OF ANGLE OF TWIST OF SHAFT WITH KEYWAY TO ANGLE OF TWIST OF SIMILAR SHAFT WITHOUT KEYWAY.

Diameter of Shaft inches	Dimensions of Keyway			
	$w = 0.25$ $h = 0.125$	$w = 0.25$ $h = 0.1875$	$w = 0.50$ $h = 0.125$	Woodruff System*
1¼	1.24	1.25	1.27	1.11
$1\frac{9}{16}$	1.14	1.24	1.19	1.11
	1.18	1.21	1.36	1.18
$1\frac{15}{16}$	1.16	1.21	1.41	1.11
	1.29	1.48	1.54	1.12
2¼	1.10	1.25	1.18	1.05
	1.10	1.28	1.37	1.10
Average	1.17	1.27	1.33	1.11

*See Table 4 for sizes of Woodruff Keyways.

12. *Effect of Keyway on Stiffness of Shaft.*—The amount of twist in a shaft transmitting power is frequently of importance. Table 3 gives the ratio of angle of twist of shafts with keyways to angle of twist of shafts without keyways as computed from the data of the torsional tests for stresses within the elastic limit. The results are fairly well represented by the equation

$$k = 1.0 + 0.4\,w + 0.7\,h,$$

in which k = ratio of angle of twist of shaft with keyway to angle of twist of similar shaft without keyway, w = width of keyway ÷ diameter of shaft, and h = depth of keyway ÷ diameter of shaft.

Keyways for two Woodruff keys of shearing strength sufficient to develop the full twisting strength of shaft seemed to reduce the stiffness of the shaft somewhat less than did a keyway for a square key whose side measures one-fourth the diameter of the shaft.

In considering the torsional stiffness of a shaft, it must be remembered that the keyways reduce the stiffness only over that portion of length which they actually occupy.

13. *Efficiency of Shafts with Keyways.*—The efficiency of a shaft with keyway has already been defined as the ratio of strength at elastic limit of a shaft with keyway to the strength at elastic limit of a similar shaft without keyway.

The determination of the elastic limit of a shaft under torsion is somewhat difficult; when the outer fibers are stressed to the elastic limit, the stress is taken more largely by the inner fibers, and the change of angle of twist is not so sudden as is the change of stretch at the elastic limit in a piece under tension, where the fibers are stressed nearly uniformly, and all begin to yield at nearly the same time. In the 1908 tests, each test shaft carried only a single keyway, and comparison between the strength of shafts with keyways and the strength of similar shafts without keyways was made by testing different specimens. This allowed a comparison of the ultimate strengths, which are very clearly defined; but in comparing elastic limits, the variation between the material of different specimens was sufficiently great to throw some doubt on the accuracy of the efficiency of shafts with keyways, as determined by this method. In the 1909 tests, the elastic limit of a section of shaft with keyway was compared with that of an adjacent section without keyway in the same shaft. Thus the error due to difference in material was greatly reduced, but by this method the ultimate strength of only the weakest section of the shaft could be obtained. So while all the results on ultimate strength have been obtained from the 1908 tests, the efficiencies of the shafts with keyways have been obtained entirely from the 1909 tests.

In computing results, J. B. Johnson's method of locating the elastic limit was found most satisfactory*. Fig. 5 to 12 give the deformation and set curves for the 1909 series of tests. The solid lines show the deformation (angle of twist) under load, while the broken lines show the set. The elastic limit as determined by Johnson's method is shown on each curve by a short line drawn across the deformation curve, and it will be noted that the stress at which noticeable permanent set begins is in all cases nearly the same as the stress at the elastic limit as determined by Johnson's method.

Table 4 shows the efficiency of the various test shafts of the 1909 series of tests, using the term efficiency as previously defined. From this table it would appear that for a set of shafts of different sizes having the dimensions of the keyway kept proportional to the diameter of shaft, the efficiency does not depend, in any noticeable degree, on the size of shaft. The efficiency does not seem to be affected by the addition of a bending moment as great as the twisting moment. The efficiency of a shaft with two keyways cut in the same plane for two Woodruff keys, of such size that the strength of solid shaft was equal to the shearing strength of the two Woodruff keys, is about the same as the efficiency of a shaft with a keyway whose width equals one-fourth the diameter of the shaft and whose depth equals one-eighth the diameter of the shaft.

The results of the foregoing tests are fairly well represented by the equation

$$e = 1.0 - 0.2\,w - 1.1\,h$$

in which

e = efficiency of shaft with keyway,
w = width of keyway ÷ diameter of shaft,
h = depth of keyway ÷ diameter of shaft.

---

*J. B. Johnson's method of locating the elastic limit consists in finding the point on the stress-deformation curve at which the deformation is increasing fifty per cent more rapidly than its initial rate of increase. See Johnson's "Materials of Construction", pp. 18-20.

TABLE 4.

EFFICIENCY OF SHAFTS WITH KEYWAYS.

$$\left\{ \text{Efficiency} = \frac{\text{elastic strength of shaft with keyway}}{\text{elastic strength of shaft without keyway}} \right\}$$

Dimensions of Keyway	$w = 0.50$ $h = 0.125$	$w = 0.25$ $h = 0.1875$	$w = 0.25$ $h = 0.125$	Woodruff System*
Under simple torsion:				
Cold-rolled shaft, dia. 1¼ in.	0.762	0.760	0.820	0.840
Cold-rolled shaft, dia. $1\frac{9}{16}$ in.	0.803	0.846	0.900	0.860
	0.758	0.817	0.889	0.815
Cold-rolled shaft, dia. $1\frac{15}{16}$ in.	0.748	0.710	0.860	0.826
	0.764	0.750	0.824	0.835
Cold-rolled shaft, dia. 2¼ in.	0.848	0.775	0.839	0.943
	0.705	0.689	0.825	0.861
Under combined torsion and bending:				
1. Twisting moment = Bending moment	0.630	0.636	0.791	0.716
Cold-rolled shaft, dia. 1¼ in.	0.680	0.698	0.803	0.750
Cold-rolled shaft, dia. $1\frac{15}{16}$ in.	0.584	0.697	0.854	0.858
	0.671	0.775	.....	0.840
2. Twisting moment = $\frac{5}{3}$ Bending moment				
Cold-rolled shaft, dia. 1¼ in.	0.895	0.670	0.940	0.930
	0.870	0.735	0.888	0.880
Cold-rolled shaft, dia. $1\frac{15}{16}$ in.	0.740	.....	0.832	0.856
	0.815	.....	0.840	0.810
General Average	0.752	0.735	0.850	0.845

*In 1¼-in. shafts keyways were cut for No. 15 Woodruff keys
$1\frac{9}{16}$-in. shafts keyways were cut for No. 25 Woodruff keys
$1\frac{15}{16}$-in. shafts keyways were cut for No. S Woodruff keys
2¼-in. shafts keyways were cut for No. U Woodruff keys

This equation gives efficiencies slightly lower than those observed for keyways of small width or depth, and efficiencies about the same as those observed for keyways in which $w = 0.50$ and $h = 0.125$; or $w = 0.25$ and $h = 0.1875$. As this equation is entirely dependent on the results of experiments, it should not be used for points much outside the limits of the experiments. The limits of the above series of tests were keyways having $w = 0.50$ and $h = 0.1875$.

Fig. 13 affords a convenient graphical method of applying the above formula, and is used as follows: To determine the efficiency of a shaft with a given (or proposed) keyway, locate on the diagram a point whose vertical distance from 0 equals the value of h, and whose horizontal distance from 0 equals the value of w. This point will, in general, fall between two lines representing values of efficiency, and the efficiency of the shaft in question may then be estimated with sufficient accuracy. The space within the triangle OAB represents the range covered by the

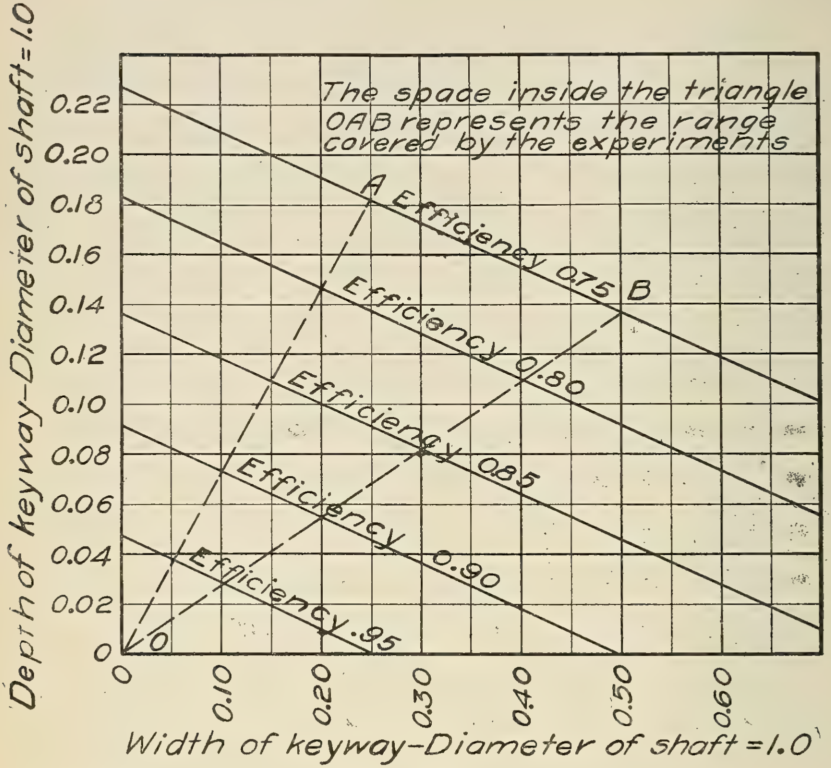

FIG. 13.

tests actually performed, and covers the proportions of keyways commonly used in practice.

14. *Torsional Strength of Shafts with Keyways.*—The object of these tests was to determine ratios of strength and stiffness between shafts with keyways and shafts without keyways. The number of tests was not sufficient to give very much information as to the properties of cold-rolled steel shafting. However, as a matter of general interest, the values found in these tests for the modulus of elasticity in shear (torsion), and of the fiber stress at the elastic limit of the cold-rolled test shafts at sections without keyway, have been tabulated in Tables 5 and 6.

Taking the fiber stress at the elastic limit of cold-rolled steel shafting at 37 500 lb. per sq. in. (a value slightly less than the average found in the tests), and the efficiency of shafts with keyways from the equation $e = 1.0 - 0.2\,w - 1.1\,h$, values for the

TABLE 5.

MODULUS OF ELASTICITY IN SHEAR (TORSION) OF COLD-ROLLED STEEL SHAFTING.

Test No.	Diameter of Shaft inches	Modulus of Elasticity
46	1¼	12 900 000
47	$1\frac{9}{16}$	12 000 000
48	$1\frac{9}{16}$	12 490 000
49	$1\frac{15}{16}$	10 800 000
50	$1\frac{15}{16}$	12 660 000
51	2¼	11 340 000
52	2¼	11 710 000
	Average	11 985 000

TABLE 6.

ELASTIC LIMIT IN TORSION OF COLD-ROLLED STEEL SHAFTING.

Test No.	Diameter of Shaft inches	Fiber Stress lb. per sq. in.
46	1¼	43 300
47	$1\frac{9}{16}$	36 800
48	$1\frac{9}{16}$	38 500
49	$1\frac{15}{16}$	36 800
50	$1\frac{15}{16}$	40 500
51	2¼	36 200
52	2¼	40 500
	Average	38 940

twisting moments and the horse-power at 100 r.p.m., transmitted by cold-rolled shafts stress to the elastic limit, have been computed for various sizes and tabulated in Table 7. These values are for shafts with keyways for square keys whose side measures about one-fourth the diameter of the shaft. In the use of this table, a suitable factor of safety should be allowed.

TABLE 7.

STRENGTH OF SHAFTS WITH KEYWAY.

The table gives the calculated twisting moment and horse-power at 100 r. p. m., transmitted in torsion by cold-rolled shafting with keyway when stressed to the elastic limit. Fiber stress is assumed at 37 500 lb. per sq. in. The keyway is cut for a square key whose side measures approximately one-fourth the diameter of the shaft. No allowance is made for bending action. In applying this table, a suitable factor of safety should be used.

Diameter of Shaft inches	Side of Key inches	Twisting Moment in.-lb.	Horse-power at 100 r. p. m.
1	¼	5 980	9.5
$1\frac{1}{16}$	$\frac{9}{32}$	7 080	11.2
1⅛	$\frac{9}{32}$	8 510	13.5
$1\frac{3}{16}$	$\frac{5}{16}$	9 980	15.7
1¼	$\frac{5}{16}$	11 680	18.5
$1\frac{5}{16}$	$\frac{11}{32}$	13 390	21.3
1⅜	$\frac{11}{32}$	15 550	24.7
$1\frac{7}{16}$	⅜	17 590	27.9
1½	⅜	20 190	32.0
$1\frac{9}{16}$	$\frac{13}{32}$	22 600	35.9
1⅝	$\frac{13}{32}$	25 660	40.7
$1\frac{11}{16}$	$\frac{7}{16}$	28 500	45.2
1¾	$\frac{7}{16}$	32 060	50.9
$1\frac{13}{16}$	$\frac{15}{32}$	35 350	56.1
1⅞	$\frac{15}{32}$	39 420	62.6
$1\frac{15}{16}$	½	43 180	68.5
2	½	47 860	75.9
$2\frac{1}{16}$	$\frac{17}{32}$	52 140	82.7
2⅛	$\frac{17}{32}$	57 900	91.1
$2\frac{3}{16}$	$\frac{9}{16}$	62 210	98.7
2¼	$\frac{9}{16}$	68 160	108.2
$2\frac{5}{16}$	$\frac{19}{32}$	73 490	116.6
2⅜	$\frac{19}{32}$	80 120	127.1
$2\frac{7}{16}$	⅝	86 080	136.6
2½	⅝	93 470	148.3

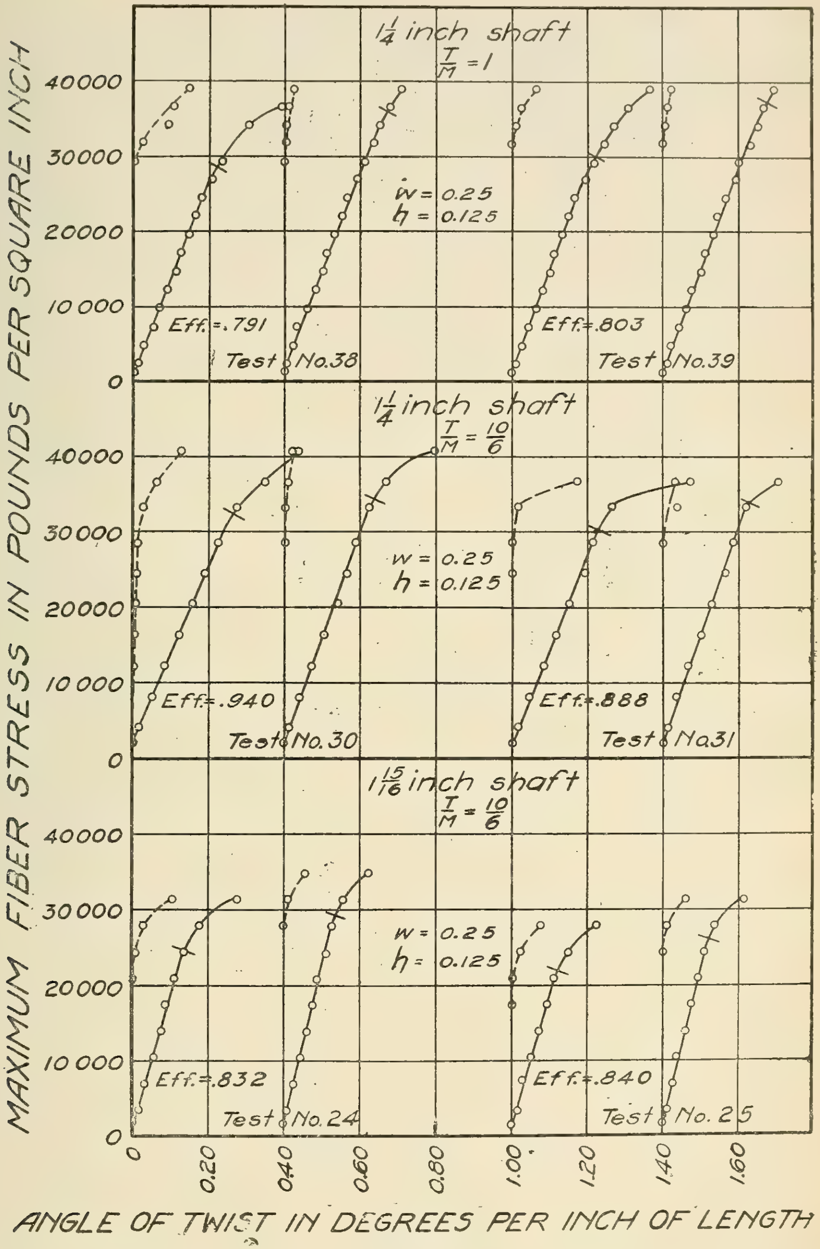

FIG. 5. DIAGRAMS OF TESTS UNDER COMBINED BENDING AND TWISTING.

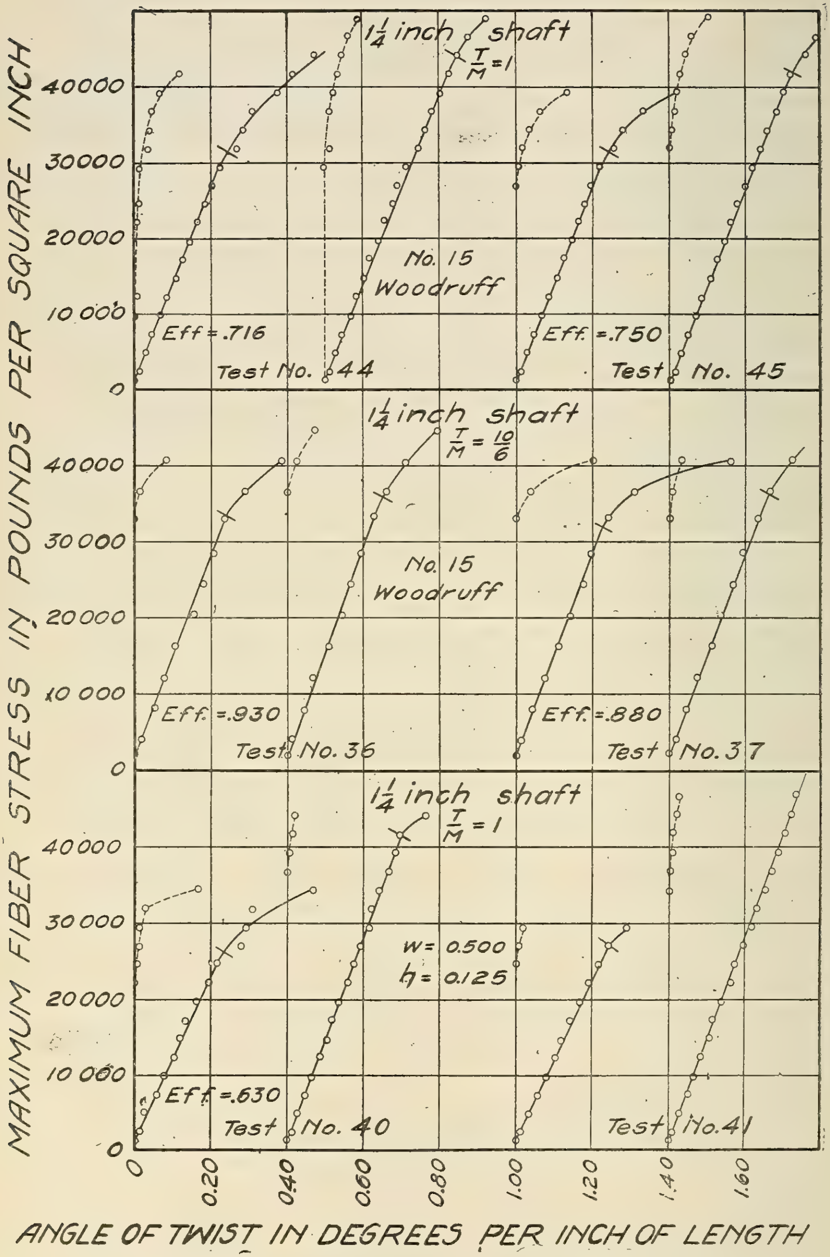

FIG. 6. DIAGRAMS OF TESTS UNDER COMBINED BENDING AND TWISTING.

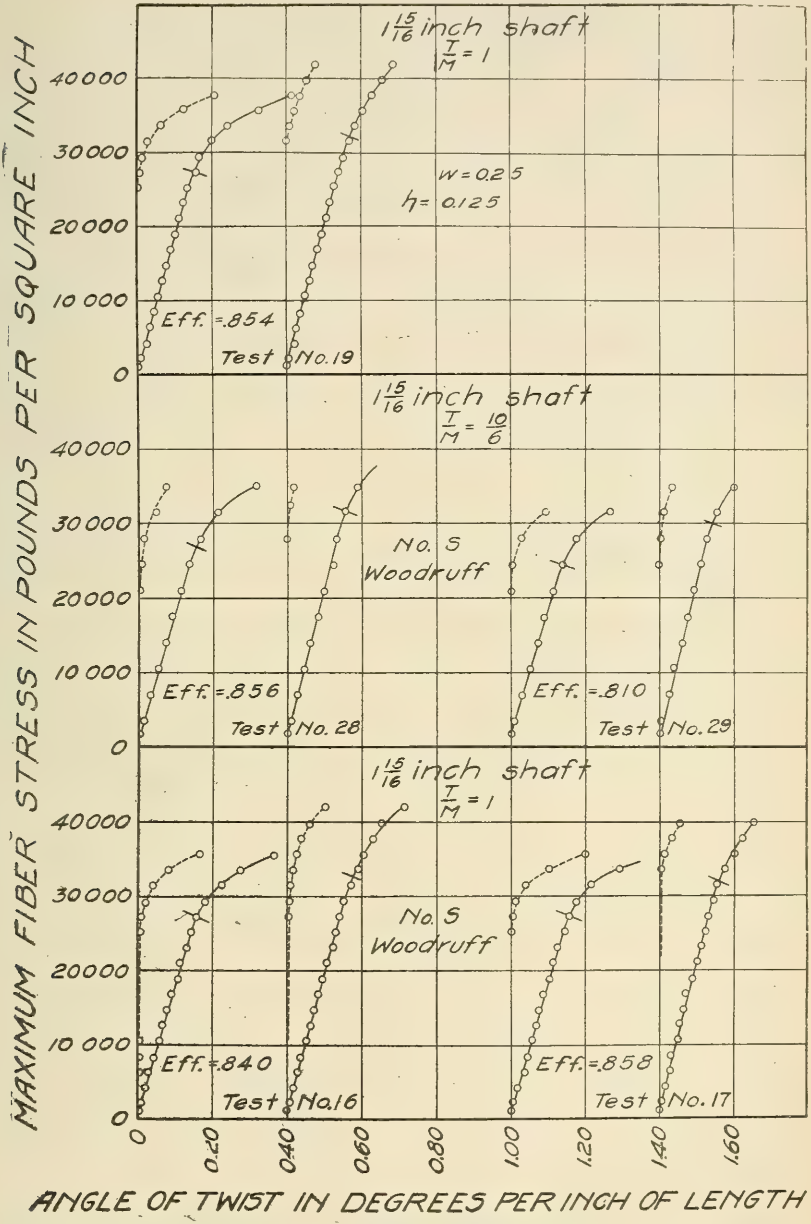

FIG. 7. DIAGRAMS OF TESTS UNDER COMBINED BENDING AND TWISTING.

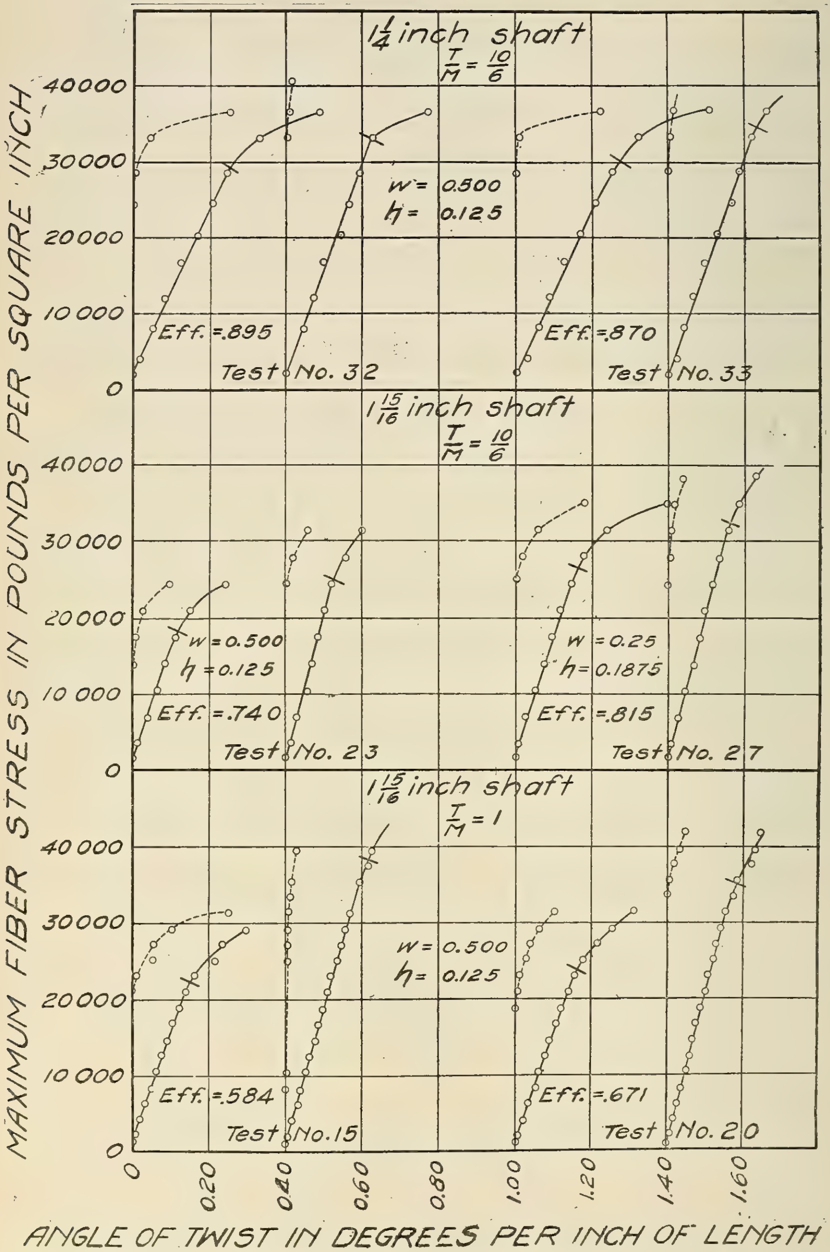

FIG. 8 DIAGRAMS OF TESTS UNDER COMBINED BENDING AND TWISTING

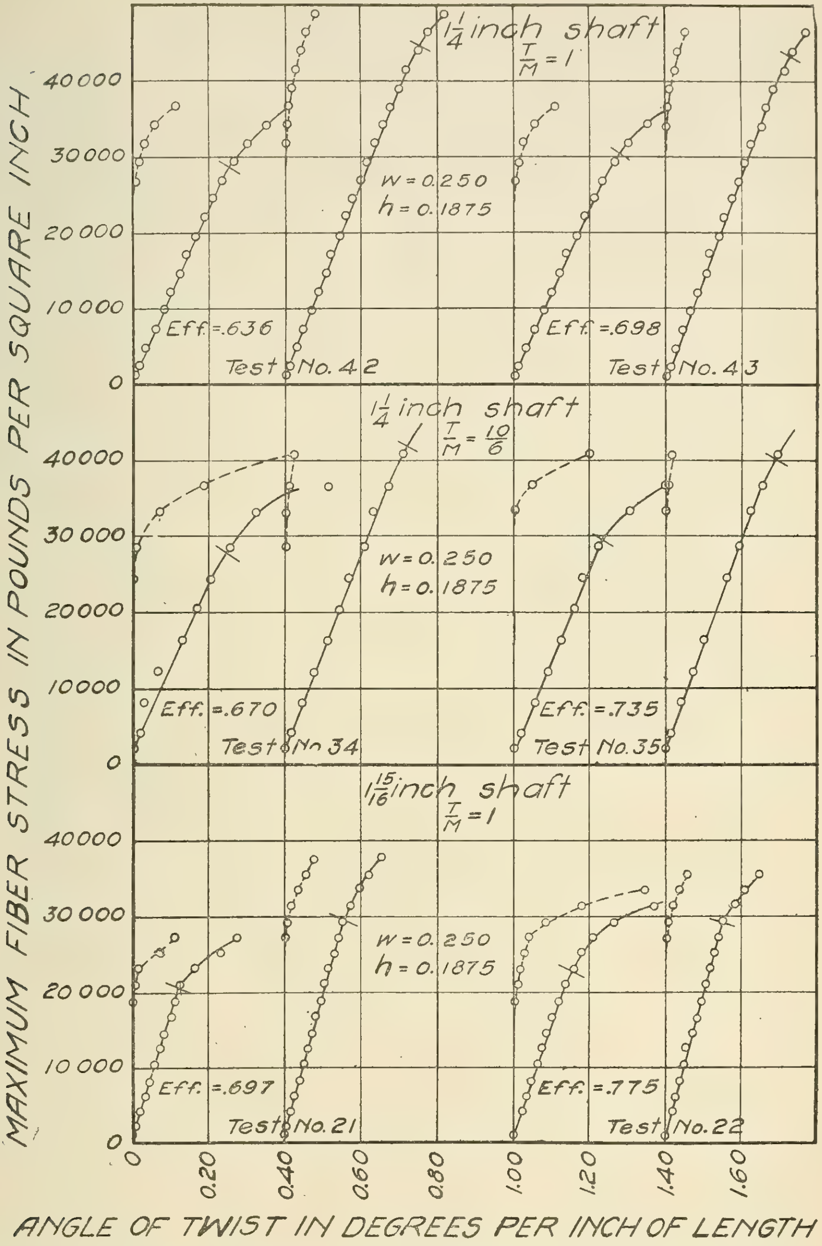

Fig. 9 Diagrams of Tests under Combined Bending and Twisting.

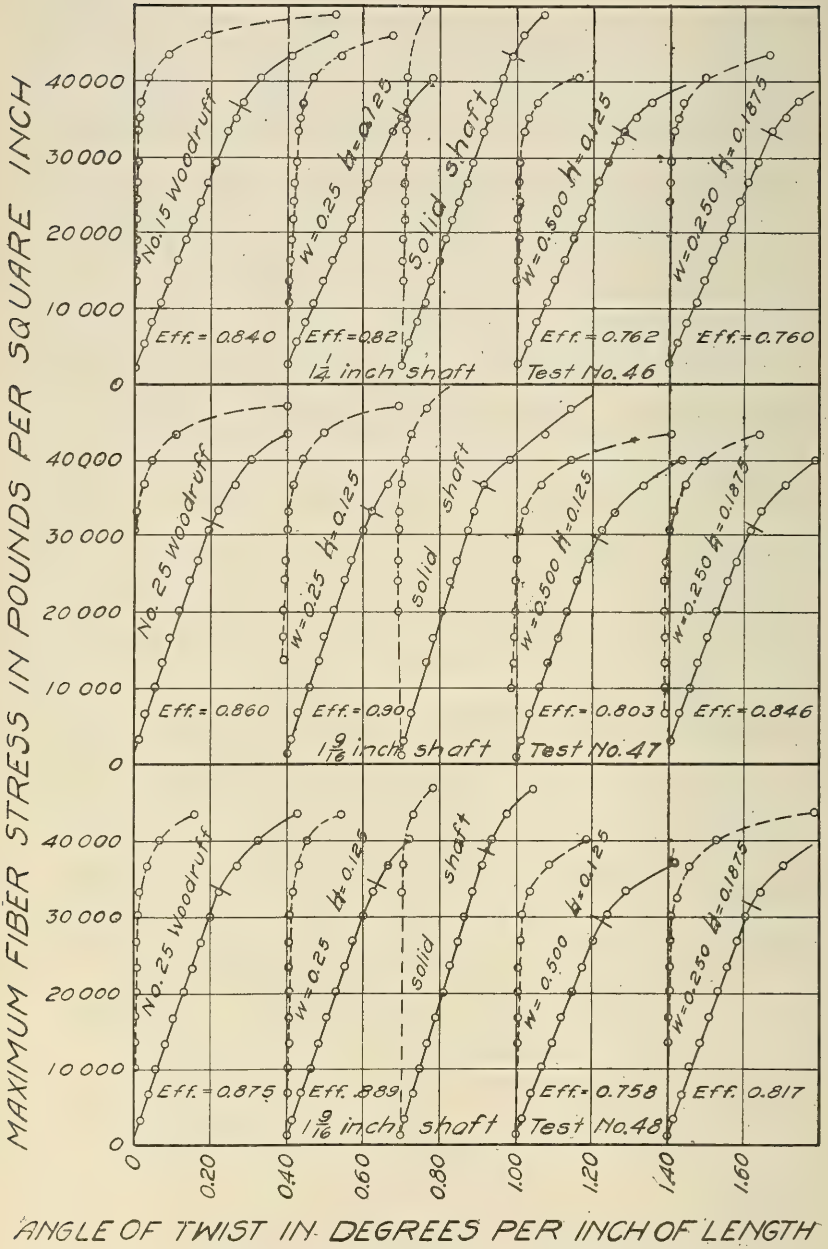

FIG. 10 DIAGRAMS OF TESTS UNDER TWISTING ONLY.

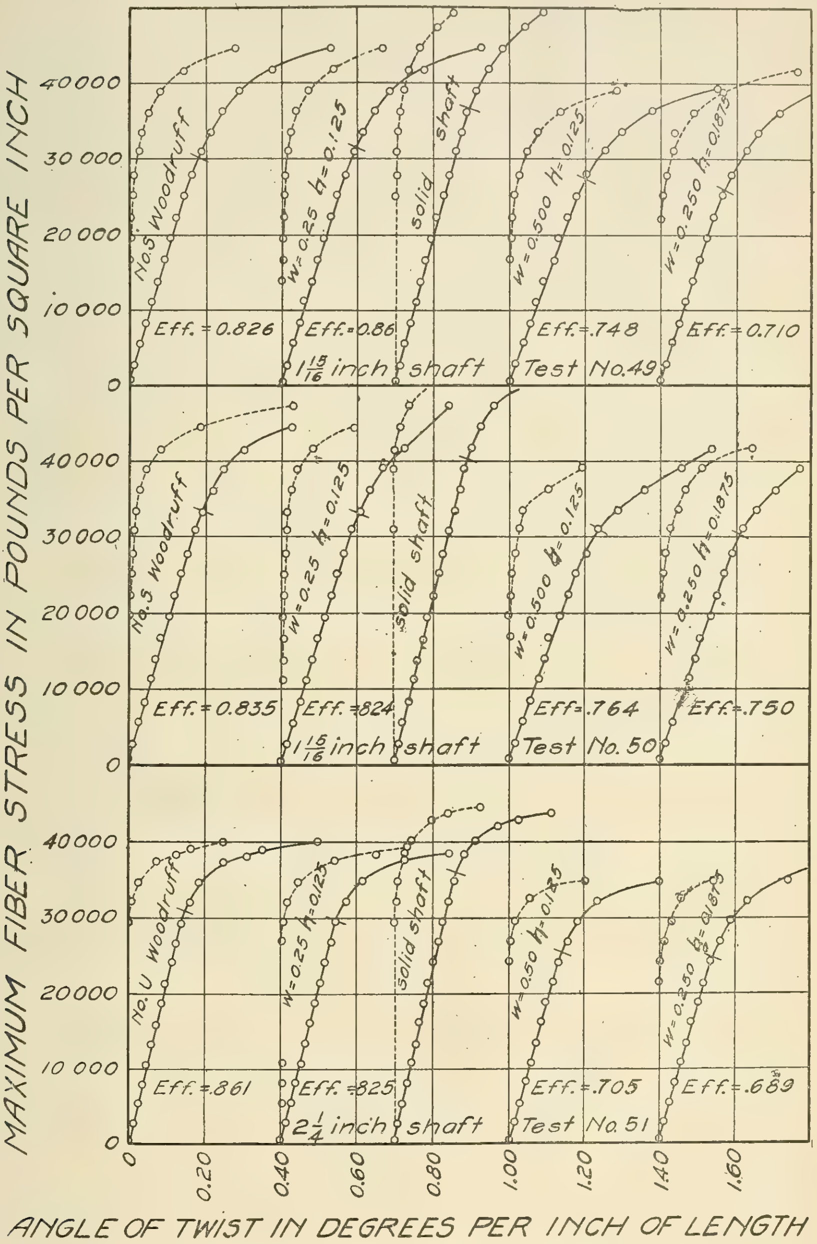

FIG. 11 DIAGRAMS OF TESTS UNDER TWISTING ONLY.

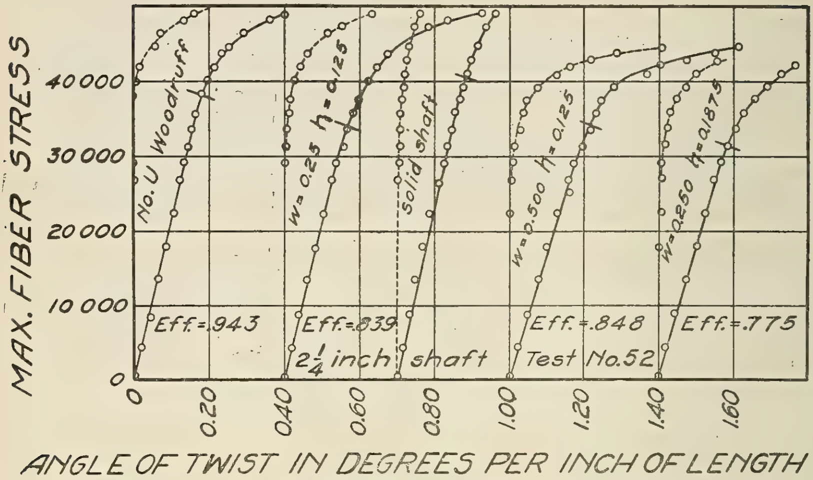

FIG. 12 DIAGRAMS OF TESTS UNDER TWISTING ONLY.

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FREIGHT TRAIN RESISTANCE

ITS RELATION TO CAR WEIGHT

BY

EDWARD C. SCHMIDT

UNIVERSITY OF ILLINOIS
ENGINEERING EXPERIMENT STATION

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PUBLISHED BY THE UNIVERSITY

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UNIVERSITY OF ILLINOIS
ENGINEERING EXPERIMENT STATION

BULLETIN NO. 43 MAY 1910

FREIGHT TRAIN RESISTANCE

ITS RELATION TO AVERAGE CAR WEIGHT

BY EDWARD C. SCHMIDT, PROFESSOR OF RAILWAY ENGINEERING

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FREIGHT TRAIN RESISTANCE:

ITS RELATION TO AVERAGE CAR WEIGHT

PART I

I. Introduction

1. *Preliminary.*—Train resistance varies not only with the train speed, but also with the average weight of the cars of which the train is composed. At a given speed the tractive effort required for each ton of weight of the train will be greater, for example, for the train which is composed of cars of 20 tons average gross weight, than for the train composed of cars which weigh, on the average, 50 tons each.

While this fact has been known for some years, it has found inadequate expression and but little application. In the establishment of their tonnage ratings, many railroads have altogether ignored it. In the tonnage ratings of a few roads, this variation of resistance with car weight is recognized to the extent of allowing a difference in rating between trains composed of loaded cars and those consisting entirely or partially of empty cars. Generally, in such systems, a certain amount is allowed arbitrarily to be added to the weight of empty cars in determining, for the purpose of rating, the weight of the train in which they are found. In such rating no distinction is made between loaded cars of various weights although such weights vary from 25 to 70 tons. A still smaller group of railroads have fully recognized the significance of the facts above stated in establishing their tonnage ratings, which, in such cases, are usually termed "adjusted" or "equated" ratings. Under these adjusted ratings, the actual weight of the train allotted to a particular locomotive varies according to the number of cars in the train. The ratings for the same locomotive, with trains of 40, 60, and 80 cars, for example, will be different in each of the three cases. This is, in effect, a variation of the rating with respect to the average car weights. Most of these adjusted ratings have been empirically determined. In the few cases where they rest upon experiments made to determine the variations in train resistance with respect to car weight, the data and results of such experiments have not been fully published.

Existing train resistance formulas likewise fail in most cases to take into account these variations of resistance with car weight, and probably much of the divergence among them is properly to be ascribed to this fact.

2. *Purpose of the Tests.*—In view of the facts just stated, it has seemed desirable to make the tests whose results are here recorded. They were planned to determine the resistance of freight trains under the usual conditions of operation; and they were designed to disclose at the same time, if possible, the relation existing, at any given speed, between train resistance and average car weight. Since the chief use of such information is in the production of locomotive ratings, the conditions of the tests have been made like those which prevail in normal freight train operation. The speed range, for example, is from 5 to 35 miles per hour; and the trains experimented upon were trains in regular service, and usual in their make-up. The track upon which the tests were made is believed to be representative of good main-line construction.

The tests have been conducted by the Railway Engineering Department of the University of Illinois as part of the research work of the Engineering Experiment Station. They were begun in April, 1908, and were completed in May, 1909. All tests were made by means of Test Car No. 17, a dynamometer car, owned jointly by the University of Illinois and the Illinois Central Railroad, and were carried out on the Chicago division of this road.

In Part I of this report, the aim has been to present as brief a statement of the results and conditions as is compatible with a clear understanding of the tests. It consists, accordingly, of a discussion of the results of the experiments, prefaced by a general statement of conditions and methods. The final results are exhibited in Fig. 11, in Table 3, and in equations 1 to 13, on pages 33, 34, and 35. A summary of the test conditions and the conclusions is inserted on pages 5 to 7. Part II of the report has been added in order to complete the record so that those interested in the details may verify or modify the results and conclusions presented in Part I. It consists of appendixes in which the aim has been to state fully all the conditions of track, weather, and train make-up, as well as to present the test data, the methods of calculation, and the results.

Throughout the report, the terms "resistance" and "train resistance" mean the number of pounds of tractive effort required for each ton of the train in order to keep it in motion on straight and level track, at uniform speed, and in still air. The report deals exclusively with the resistance of the train behind the locomotive tender. Locomotive and tender resistance are not discussed.

3. *Acknowledgments.*—The tests have been made possible through the interest and cooperation of Mr. William Renshaw, Mr. J. G. Neuffer, and Mr. R. W. Bell, who were successively superintendents of machinery of the Illinois Central Railroad, during the period of planning and conducting the work. Many other officials of the Chicago division of the road have rendered generous assistance in the investigation, which has entailed for them not a little inconvenience and labor. Such interest and assistance are thoroughly appreciated by those of the University staff who have been concerned with the work.

Throughout the tests, the operation of the dynamometer car and the making of the calculations have been under the direct supervison of F. W. Marquis, Associate in the Railway Engineering Department, Engineering Experiment Station. Much of whatever accuracy and reliability have been attained in the investigation is due to his intelligent and painstaking care in making the tests and in systematizing the work of calculation. He has also rendered great assistance in supervising the preparation of the tables and illustrations, and in the final checking of the manuscript.

II. SUMMARY AND CONCLUSIONS

4. *Summary.*—The report deals with the results obtained from tests of 32 ordinary freight trains, whose chief characteristics were as follows:

	Minimum	Maximum
Total weight, tons	747	2908
Average weight per car, tons	16.12	69.92
Number of cars in the train	26	89

The trains whose average weights were less than 20 tons or more than 60 tons were composed of cars of nearly uniform weight; while those whose average car weights were between 20 and 60 tons were either homogeneous or mixed as regards the weight of the individual cars.

The weather during the tests was generally fair. The minimum air temperature during any test was 34° F. the maximum 82° F. The approximate average wind velocity prevailing throughout one test was 25 miles per hour; during all the others it was less than 20 miles per hour.

The tests were made upon well-constructed and well-maintained main-line track, 94 per cent of which is laid with 85-lb. rail, the remainder being laid with 75-lb. rail. Except through station grounds, where screenings or cinders are used for ballast, the track is full ballasted with broken stone.

5. *Conclusions.*—The results of the tests are presented in Fig. 10 and 11, pp. 31 and 33, in Table 3 on p. 35, and in the equations on p. 34. The curves, the table, and equations are each different expressions of the same facts. It is believed that by their use the probable total resistance of *entire* freight trains at various speeds may safely be predicted, when running upon straight and level track of good construction, during weather when the temperature is above 30° F., and the wind velocity is not more than 20 miles per hour, provided the *average* weight of the cars composing the train be known.

The results are applicable to trains of all varieties of make-up to be met with in service. They may be applied, without incurring material error, to trains which are homogeneous and to those which are mixed as regards individual car weight.

The results are primarily applicable to trains which have been in motion for some time. When trains are first started from yards, or after stops on the road of more than about 20 minutes' duration, their resistance is likely to be appreciably greater than is indicated by the results here presented. In rating locomotives, no consideration need be given this matter, except in determining "dead" ratings for low speeds, and then only when the ruling grade is located within six or seven miles of the starting point or of a regular road stop.

It is to be expected that some trains to be met with in service will have a resistance about 9 per cent in excess of that indicated by Fig. 10 and 11, due to variations in make-up or in external conditions within the limits to which the tests apply. If operating conditions make it essential to reduce to a minimum the risk of failure to haul the allotted tonnage, then this 9 per cent allowance should be made. This consideration, like the one preceding, is important only in rating locomotives for speeds under 15 miles per hour. At higher speeds, the occasional excess in the resistance of individual trains will result in nothing more serious than a slight increase in running time. It should be emphasized that this allowance, if made, is to be added to the resistance on level track—not to the gross resistance on grades.

III. The Methods and Means Employed in Conducting the Tests

6. The tests were carried on by means of the dynamometer car referred to as Test Car No. 17, which, when not in use, is held at Champaign, a district terminus. The car was operated from time to time in the regular trains leaving this point, and the trains selected were partly in the northbound, partly in the southbound traffic.

The plan was to determine, for each of the trains experimented upon, the relation of its resistance to its speed. This information was to be expressed finally as a resistance-speed curve such as is shown in Fig. 1 and in the various figures given in Appendix 5. The trains were so selected that their average car weights would vary throughout as great a range as possible. As will later appear, this range proved to be from the weight of an empty gondola to that of a fully loaded car of 100 000 lb. capacity. It was the expectation that when the resistance-speed curves of the individual tests were brought together, their analysis would reveal the relations existing between train resistance and car weight.

7. During each test the following information was obtained:

(*a*) The drawbar pull of the locomotive upon the train.

(*b*) The train speed.

(*c*) A continuous record of the time elapsed from the beginning of the test.

(*d*) The pressure existing in the brake cylinder of the test car.

(*e*) The direction of the wind relative to the direction of motion of the car.

(*f*) The velocity of the wind relative to the car.

(*g*) A record of the location of the test car upon the road.
(*h*) Air temperatures and other weather conditions.
(*i*) Data concerning the train, such as its weight, etc.

The information cited under items (*a*) to (*g*) was obtained in the form of continuous graphical records upon the chart which is produced by the apparatus of the dynamometer car. By means of this chart any of the quantities mentioned may be determined at any point upon the road.

The curves of draw-bar pull and speed provide the information essential to the investigation. Supplemented by an accurate profile and a record of train weight, they enable net train resistance to be calculated at any position of the train upon the road. The time record provides a means of calibrating and checking the speed curve. The pressure in the brake cylinder was recorded merely to make it possible to distinguish those periods during the test when the brakes were applied to the train; it being obviously necessary to ignore such portions of the record when making the calculations. The relative wind velocity and relative wind direction were obtained by means of an anemometer and a wind vane mounted on the roof of the test car. When compounded with the known speed and direction of motion of the car, these data permit the determination of the actual wind direction and wind velocity with respect to the track. In Appendix 5, for each test, there are recorded this actual wind velocity and actual wind direction with respect to the track for each point at which train resistance was determined. It is probable that these wind data are, under some circumstances, subject to a considerable error. Considering the length of the run made with each train and the length of time it was on the road, it is believed that the wind data thus obtained are, nevertheless, more reliable than those which might have been recorded by stationary instruments located at one or two points along the track. Item (*g*), the location of the car upon the road, was defined by marking upon the test car record the position of mile posts and stations at the moment they passed the car. By means of this record, it is possible to correlate any position of the train with the road profile. Data concerning the train were obtained by one or two observers who had no other duties. With the one exception noted beyond, all trains were weighed, to determine their tonnage. In addition to its weight, there was recorded for each train, its length[1], and for each car, its number, kind, stenciled "light weight", gross weight, capacity, and the initials of the owning road.

All test car instruments were calibrated before the tests, and their calibrations were frequently checked during the progress of the investigation. All observers were men experienced in the operation of the test car and many of them had participated also in the work of calculation and were consequently aware of the points at which alertness and care were especially needed. No effort has been spared, in conducting the tests, to insure accuracy in the data. These facts are here mentioned as having some significance to any one who may undertake to estimate the reliability of the results. Appendix 1 contains an illustration of one of the test car charts and a detailed description of the car itself.

This report includes the data and results from tests of 32 different trains. For the purposes of this research, tests were made of twelve other freight trains; but their results were finally excluded from the report. Three of these additional tests were rejected because of uncertainty about the train weights; one, because of a break-down in the test car recording apparatus during the progress of the test; and eight were disregarded because the temperatures prevailing were below the range for which it was intended the results should apply, the low temperature in some cases being coupled with high wind.

IV. Test Conditions and Train Data

8. *The Trains Tested.*—The test trains were all of such make-up as naturally resulted from the traffic conditions in the Champaign yards. For most of the tests the test car was simply coupled into the trains selected by the trainmaster, solely with reference to his convenience in operating and in returning the test car. As the investigation progressed, it became apparent that the accumulated data left certain gaps in the range of average car weights. There were at this stage, for example, few trains experimented upon with average car weights near 25 to 30 tons, and none with an average car weight of 70 tons. The last six or eight

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[1] Train length was determined by counting, during the test, the number of rail lengths corresponding to the length of the train and multiplying this number by 30 feet, which is the rail length for this track.

trains were therefore made up especially to supplement the data at these points. It should be understood, however, that nothing in this process resulted in a train make-up which was in any respect unusual. All the trains tested are, therefore, such as one might expect to find upon any road where the traffic conditions are normal. They include trains made up almost entirely of empty gondolas[1], others with considerable variation in both load per car and kind of car, and still others composed almost entirely of loaded box cars or of loaded gondolas.

Test S-1018 demands special mention in this connection. The train for this test included Illinois Central Railroad locomotives No. 423 and No. 732, weighing respectively 145 200 and 223 600 lb. Their combined weight constituted 13.6 per cent of the total train weight. These locomotives with their tenders were being hauled "dead" and had the main rods disconnected, as is usual in such cases. The first is of the 2-6-0 type, the second of the 2-8-0 type, and they and their tenders had therefore together 17 axles in operation. For the purpose of determining the average car weight for this train, these two locomotives were assumed to be equivalent, in their resistance, to a number of cars having a like number of axles, i. e., 4¼ cars. The results of the calculations warrant the belief that this view of the situation has resulted in no material error. A study of Table 1 will make clear the diversity in the composition of the trains.

All trains except No. S-1016, S-1018, S-1030A, and S-1030B were weighed upon one of the two track scales at Champaign. This weighing was done in the usual manner, by pulling the train over the scales and weighing the cars successively without uncoupling them. These track scales were in good condition and were each inspected four times during the test period. These inspections disclosed a maximum error in one scale of $-\frac{1}{5}$ per cent, in the other of $-\frac{1}{2}$ per cent. The train in test S-1016, composed entirely of empty cars, by an error in arrangements, left the yards without being weighed. The weights stenciled on the cars were accepted as correct in this case. The train in test S-1018 was weighed upon track scales in the Chicago yards; and the trains of tests S-1030A and 1030B were weighed in the yards at Centralia. In test S-1021, after leaving the yards, two cars were added to the train, for which the weights were determined from the stenciled weights and the way-bills. In tests S-1030B and S-1048 the weights of one and two cars respectively were similarly determined, and in test S-1061 the stenciled weight was used for one empty car. Obviously no important errors in the total tonnage have resulted from possible inaccuracies in the weights of these cars.

---

[1] In all parts of the report except Appendix 2, cars are designated as box, stock, gondola, flat, and tank cars. The term box car is made to include refrigerator cars, the test car and the caboose. The term gondola includes all unroofed cars with sides, such as coal cars, hopper cars, etc. In the tonnage records in Appendix 2, further distinctions are made.

All cars of all trains were of course provided with the usual four-wheeled truck. Presumably the majority of the cars had journals conforming to the specifications of the Master Car Builders' Association, which for some years have required that freight car journals be either $3\frac{3}{4}$ in. by 7 in., $4\frac{1}{4}$ in. by 8 in., 5 in. by 9 in. or $5\frac{1}{2}$ in. by 10 in. in size, depending upon the car capacity. It is safe to assume that all trucks were provided with wheels of 33-in. standard diameter.

Throughout each test, observations were repeatedly made to discover such irregularities as hot journal boxes, brakes which were not free from the wheels, and trucks which did not freely follow the track. Such things occurred to the usual extent; a hot-box or two or an unreleased brake being occasionally found on some of the trains, while others were entirely free from such defects. The record of such matters was given consideration in making the calculations; but, as was anticipated, the results showed no discrepancies which could be explained by such causes.

The range over which the train data for all of the tests varied is as follows:

	Minimum	Maximum
Total train weight, tons	747	2908
Average weight of cars composing the train, tons	16.12	69.92
No. of cars in the train	26	89
Train length, feet	1120	3480

Complete information concerning each train is given in Appendix 2.

9. *The Track.*—The track upon which the experiments were carried on extends from Gilman to Mattoon, Illinois, a distance of 91 miles, and lies upon the Chicago division of the main line of the Illinois Central Railroad. Until about ten years ago this was a single track road, and one of the oldest in the State. At that time a second track was constructed, and the roadbed for both tracks is now well settled and in good condition. The maxi-

TABLE 1

A SUMMARY OF TEST CONDITIONS AND TRAIN DATA

Test No. Laboratory Serial No.	Test Date	Weather Conditions						Train Data										
			Air Temperature Degrees F.		Average Approximate Wind Velocity miles per hour	Range of the Direction of the Wind with Respect to the Track		Train Length, feet	Weights		Total Number of Cars in the Train	Train Make-Up						
			At Beginning of Test	At End of Test		From	To		Gross Train Weight tons	Average Gross Weight Per Car tons		Conditions of Loading			Kind of Cars—In Percentages of the Total Number of Cars			
												Number of Empty Cars	Number of Loaded Cars	Loaded Cars in Percentage of Total Number	Box Cars per cent	Gondola Cars per cent	Flat Cars per cent	Tank Cars per cent
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
S-1013	4-27-08	Wet	42	44	19	+35°L	90°L	2784	2549	38.04	67	10	57	85	82	13	0	5
S-1015	4-29-08	Fair	40	48	10	+25°L	−80°L	2520	2489	36.08	69	8	61	88	68	6	16	10
S-1016	4-30-08	"	44	48	10	+15°R	+60°R	3030	1161	16.12	72	72	0	0	3	97	0	0
S-1017	5- 1-08	Wet	48	54	16	+45°L	−80°L	2670	2532	38.44	66	13	53	80	95	5	0	0
S-1018	5- 2-08	Fair	40	45	11	+10°R	+85°R	2130	1353	25.40*	49*	34	15	31	61	6	16	17
S-1019	5- 9-08	"	44	62	25	+20°R	+45°R	3480	1572	17.72	89	75	14	16	34	58	7	1
S-1021	5-13-08	Wet	66	70	17	+60°R	+80°R	2400	2908	46.16	63	10	53	84	32	60	5	3
S-1023	5-23-08	Fair	62	74	17	+75°R	−80°R	2320	2243	38.72	58	17	41	71	45	52	0	3
S-1027	7- 2-08	Wet	64	80	14	−50°R	+70°R	1710	2185	47.44	46	3	43	94	22	76	2	0
S-1030A	7- 8-08	Fair	60	68	6	+20°R	+65°R	1380	2036	59.88	34	2	32	94	6	94	0	0
S-1030B	7- 8-08	"	68	72	7	+20°R	+65°R	1650	2342	57.12	41	3	38	93	20	80	0	0
S-1031	7-22-08	"	70	82	5	+ 0°	+40°L	1425	747	20.72	36	30	6	17	94	3	3	0
S-1033	9-26-08	"	66	82	12	+ 5°L	+15°R	1710	2275	51.70	44	2	42	95	5	95	0	0
S-1034	10-3-08	"	42	60	4	— 0°	+85°L	3015	1259	16.56	76	76	0	0	1	99	0	0
S-1036	10-10-08	"	40	62	6	+15°R	−15°R	2010	1961	37.72	52	8	44	85	73	25	2	0
S-1038	10-15-08	"	58	72	16	+ 5°L	+25°L	1650	2144	52.28	41	3	38	93	22	78	0	0
S-1040	10-24-08	Wet	57	53	11	+15°R	+40°R	1830	2152	45.76	47	2	45	96	49	49	0	2
S-1043	11-7-08	Fair	38	53	8	+ 5°R	+65°R	2580	1118	16.92	66	65	1	2	24	74	0	2
S-1048	11-28-08	"	36	39	6	+ 5°R	+30°L	a2175	2443	45.24	54	8	46	85	37	63	0	0
								b2100	2355	45.24	52	8	44	85	38	62	0	0
S-1050	1-23-09	"	53	66	8	+ 0°	−25°R	1620	1618	40.44	40	16	24	60	75	25	0	0

S-1052	1-28-09	Wet	36	40	11	—45°L	+70°L	2430	1514	24.80	61	44	17	28	61	38	1	0
S-1057	3- 6-09	Fair	34	40	10	+20°R	—35°L	1830	2107	41.32	51	8	43	84	49	43	6	2
S-1061	3-13-09	"	41	38	7	+45°L	—85°L	1785	2252	51.20	44	3	41	93	5	84	11	0
S-1063	3-19-09	Wet	39	40	12	+20°R	+40°R	3060	1484	20.04	74	70	4	5	7	93	0	0
S-1070	4-17-09	Fair	58	71	4	+ 0°	—65°L	2400	1622	24.60	66	49	17	26	58*	42	0	0
S-1072	5- 1-09	"	35	37	17	+70°L	90°L	1200	1859	66.40	28	1	27	96	4	96	0	0
S-1073	5- 4-09	"	53	63	10	+25°L	+70°R	1200	1880	67,16	28	1	27	96	4	96	0	0
S-1074	5- 7-09	"	45	60	10	+65°L	—80°L	3180	1340	16.56	81	81	0	0	2	98	0	0
S-1076	5-11-09	"	51	67	16	+40°R	+75°R	1120	1818	69.92	26	1	25	96	4	96	0	0
S-1077	5-14-09	"	64	70	13	—25°R	—75°R	2145	1505	28.40	53	35	18	34	74	26	0	0
S-1079	5-18-09	"	65	68	18	+65°R	—85°R	2070	1685	33.04	51	14	37	73	90	10	0	0
S-1080	5-21-09	"	50	70	11	+ 0°	+45°L	2550	1347	21.40	63	57	6	10	16	84	0	0

Notes: 1. Columns 7 and 8—Direction is designated by the angle made with the track. A wind any component of whose velocity helps the train forward is marked +; winds with opposing velocity components are marked—. Winds from the right side of the track are designated as R, from the left side as L. Thus + 40°R means a wind blowing from the rear and from the right hand side, whose direction makes an angle of 40° with the track.

2 *Columns 11 and 12—Train has two "dead" locomotives and tenders in addition to cars noted.

3. *Column 16 –includes 15 stock cars classed as box.

4. All data apply to the train only—engine and tender are excluded.

5. Columns 9 to 19: a.—from Champaign to Rantoul; b.—from Rantoul to Gilman.

mum grade against northbound traffic is 29 ft. per mile and against southbound traffic, 31.9 ft. per mile. In all the 91 miles there are only 7850 ft. of curved track.

Through station grounds the tracks are ballasted with screenings or cinders; all other portions of both tracks (about 83 of the 91 miles) are full ballasted with broken limestone. The crossties are of oak, laid 20 in. center to center. About 10¼ miles of the west track are laid with 75-lb. A. S. C. E rail, put down in 1894 and 1895; while the remainder of the west track and all of the east track are laid with 85-lb. A. S. C. E rails, the oldest of which was put down in 1900. During eight months of the year there is employed in maintaining this portion of the road a force of men which averages one man per mile of track; during the other four months this force is reduced to one man for each two miles. Further details concerning the track are given in Appendix 3. As regards both its construction and maintenance this track is such as one may expect to find upon the main lines of first-class railroads.

These 91 miles of track were especially surveyed, immediately preceding the tests, by the Railway Engineering Department of the University for the purposes of this and similar investigations. The levels were run on the east track and readings were taken to 0.1 ft. at stations 300 ft. apart; and turning points were taken at every fourth station where levels were read to 0.01 ft. The results of the survey are expressed in a profile drawn to a scale of ¼ in. to 100 ft., which was used in making the test calculations.

10. *The Weather Conditions.*—In Table 1 the weather prevailing during each test is designated as either fair or wet, wet weather meaning either continuous or intermittent rain. During 7 of the 32 tests the weather was wet. The lowest air temperature recorded at any time during any test is 34° F.; and the highest recorded temperature is 82° F.

The column headed "average wind velocity" in Table 1 presents the averages of the calculated wind velocities derived for each point or section of the test in question for which the train resistance was determined. An inspection of the tables in Appendix 5 shows a considerable variation between the wind velocities at different points during the same test. The approximate maximum average wind velocity prevailing during any test was 25 miles per hour; the minimum was 4 miles per hour. The actual wind direction (with respect to the track) varied during the tests, as would be expected, through the entire 360°. The tables in Appendix 5 show this direction for each point at which train resistance was computed; but it seems impossible to make any useful generalization of the data there presented.

It was intended to so select the tests that the weather conditions, the temperatures, and the wind velocities would be such as usually prevail in most parts of the country from the middle of spring until the middle of autumn when the basic or "summer" tonnage ratings are in force—such conditions, in short, as would give rise to no appreciable difficulties in train operation.

V. Methods Employed in Calculating the Results.

11. The immediate purpose in making the calculations was to produce for each test a curve showing the relation between resistance and speed, for as great a variety of speeds as the data would permit. This involves calculating the train resistance at various positions of the train upon the track, and the first step towards this end is the inspection of the test car record in order to select suitable points or sections at which the resistance may be calculated. The considerations of first importance in this selection are that the points represent finally as great a speed range as possible, and that the speeds be approximately evenly distributed within this range. Points and sections were selected only where the entire train was running and continued to run upon straight track; resistance due to track curvature is therefore entirely eliminated. The data essential to the process of calculation are the draw-bar pull of the engine, the train speed and its acceleration, the tonnage, and the profile. The pull and the speed, as previously stated, are determined from continuous curves drawn on the test car chart. Two processes have been used, designated here as Method 1 and Method 2. By Method 1, the momentary values of pull, speed, acceleration, and grade were determined for a particular position of the train upon the road; by Method 2 the average values of these quantities were determined for the period during which the test car was passing over a definite section of the track.

12. *Method 1: Resistance at a Point on the Road.*—The point having been chosen, the pull and the speed were found by direct

readings from the chart. This pull divided by the tonnage gives the gross train resistance at this speed, and this gross resistance was next corrected for both acceleration and grade resistances. The acceleration was determined by graphical methods from the speed curve, and the grade was found by correlating the train's position with the profile. The points were all so selected that at the moment under consideration, the entire train was on a nearly uniform grade. Method 1 results in momentary values of train resistance at the points considered.

13. *Method 2: Average Resistance Over a Section.*—By this method the average value of train resistance was determined for the period during which the test car at the head of the train was passing a selected section of the track. This track section corresponds to a certain length or section on the test car record. It was so selected that the speed of the car when entering was nearly equal to its speed at exit, and further so that no considerable variations in speed occurred during transit over the section. The sections chosen have varied in length from about $\frac{1}{4}$ mile to 1 mile. The variations in speed in passing the section have generally amounted to less than 2.0 miles per hour, and the maximum variation over any selected section is 11.7 miles per hour. In only 58 cases out of a total of 560 does this speed variation exceed 5.0 miles per hour. These portions of the chart having been chosen, the average pull was next found by determining the average ordinate of the curve of draw-bar pull, and the average speed was found by means of the section length and the time record. Gross resistance in pounds per ton was next derived by dividing this value of pull by the tonnage, and this gross resistance was then corrected for the resistances due to acceleration and grade, as in Method 1.

In this case the average acceleration is found by consideration of the speeds at entrance to and exit from the section. In order to correct for grade, the elevation of the center of gravity[1] of the train was determined for that position of the train at which the test car entered the section, and again for the position at which the car left the section. The difference between these elevations establishes the effective average grade, which either helps or opposes the locomotive while the train passes the section. These elevations of the center of gravity of the train may not be determined with sufficient accuracy unless the train at the moment is on a practically uniform grade. The section limits were therefore so chosen.

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[1] The location in the train of its center of gravity was determined thus: Assume a train which weighs 1800 tons, is 2400 feet long, and is composed of 60 cars. By inspection of the tonnage record we find that one half of this weight (900 tons) lies in the first 25 cars. Hence the center of gravity is located $\frac{25}{60} \times 2400 = 1000$ ft. from the front end.

Method 2 results in a value of *average* train resistance for the *average* speed at which the train passes the section under consideration. It would be rigidly correct if train resistance varied uniformly with speed, in other words, if the curve showing the relation of resistance to speed were a straight line. This, of course, is not the case, and the process therefore gives results which are slightly in error. However, as stated above, the section was so chosen that the difference between the speeds at entrance to and exit from the section was small; and for the speed range represented by this difference, the curve of train resistance deviates but little from a straight line. Such error as does result from the process is, therefore, very small and is of no moment whatever when compared with variations, due to natural causes, which occur in the resistance itself.

14. *Comparison of the Two Methods.*—The two methods are fundamentally alike. Although the first is the less laborious, it requires the determination of acceleration at a point on the speed curve, which it is sometimes difficult to make accurately. For this reason the second method is generally preferable. Method 2 is also to be preferred because it deals with average values and therefore tends to eliminate from the results the incidental momentary variations which occur in the resistance itself. Consequently, the second method has been employed whenever possible, and the first method has been resorted to, as a rule, only in those cases where the limitations imposed in the selection of sections for Method 2 would have resulted in too few values from which to plot the resistance curves. Of all the individual resistance values incorporated in the report, only 32 per cent were determined by Method 1. The care exercised in the calculations, and a study of the plotted values obtained by both processes, seem to warrant the conclusion that their results are equally reliable. In Fig. 1 and in the figures in Appendix 5, the circles represent values derived by Method 1, and the circular black spots represent values obtained by Method 2.

15. *General Considerations.*—Even in freight train operation the tractive effort required to produce acceleration in the speed is frequently greater than that required to overcome all other resistances combined. To produce, for example, an acceleration of 0.1 mile per hour per second, requires a tractive effort of about 9 lb. per ton, in addition to that required by net train resistance and grade resistance. Since the acceleration resistance may constitute so large a proportion of the gross resistance, it is important that its determination be made with great care. This fact has been impressed upon all who were concerned with these tests. In calculating the acceleration resistance, both the force required to produce acceleration in the rotation of the wheels and axles, and the force required to produce the acceleration in the motion of translation of the train as a whole were determined.

The test car records make it possible to distinguish those portions of each test where the brakes were applied. Such places, few in number, were of course avoided in selecting points and sections for determining resistance. The records also show where hot-boxes and unreleased brakes were discovered in the train, and such defects were given consideration in making the calculations. They occurred infrequently and their effect could not be distinguished in the results. While therefore such portions of the record were avoided if convenient, sections and points on the charts, otherwise suitable for calculation, were not rejected on these accounts.

16. *The Effect of Stops in Limiting the Selection of Points and Sections.*—Early in the progess of this work, when low air temperatures were first encountered, it became apparent that when the train was first started from rest, its resistance, calculated for a number of points at which the speed was the same, was occasionally unusually high. This was true not only for those portions of the run made immediately after leaving the yards; but also for those portions immediately following stops on the road. In a certain test, for example, the values of net resistance, calculated at various points, at all of which the speed was 20 miles per hour, varied between 6.8 lb. and 5 lb. per ton—a difference of 27 per cent—for points selected within the first 9 miles of the run; whereas values of resistance at the same speed, determined later in the test, differed by only 10 per cent. The air tem-

perature during this test (not included in the report) varied between 22° and 26°.

For a number of tests such resistance values were plotted with respect to the distances from the yards of the points to which they apply. This process disclosed a surprisingly regular decrease in the resistance until a distance of approximately ten miles was reached, after which the resistance had settled down to a fairly uniform value. Similar variations were found to occur to some extent during tests when the air temperature was as high as 50° or 60°. This study[1] led to the conclusion that this difference in resistance was due to variations in the conditions of lubrication of the car journals, and that such variations were chiefly caused by changes in journal temperature. All this is, of course, in accord with the common belief of those experienced in train operation. The reason for discussing it in this place is that the facts stated have influenced the procedure in making calculations for this series of tests.

Since the variations in resistance are so great during the early part of the run, no point or section has been selected for calculation within about the first ten miles of any test. If other points or sections, located farther from the start, were near stops, such points were rejected unless further investigation proved that at these places the train resistance had become nearly uniform in value. Fortunately, the operating conditions were such as to entail few stops on the road, and the selection of points and sections for the calculations has not been unduly limited on these accounts[2].

The effect of these limitations is to make the results of this investigation primarily applicable to trains which have been in motion for some time. Since, however, stops are not usually made upon ruling grades,and since if stops are made at other places on the road, the locomotive has available tractive power in excess of the requirements, the results of these tests are generally applicable in the solution of tonnage rating problems, except where the ruling grade occurs near a yard or other point where the trains are made up. In such cases the tonnage determined from the resistance curves here presented may prove to be somewhat too great.

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[1] Further investigation of this matter is in progress, and the results will probably be published soon.

[2] During the 32 tests included in the investigation only 68 stops, all told, were made after leaving the yards. Of these, one was of 55 minutes duration, nine lasted between 20 and 40 minutes, twenty-two between 10 and 20 minutes, and thirty-six less than 10 minutes.

17. *The Derivation of the Resistance Curves.*—The calculations result, for each test, in a series of values of net train resistance at a variety of speeds. These values of resistance were plotted with respect to speed, and gave such a diagram as in Fig. 1.

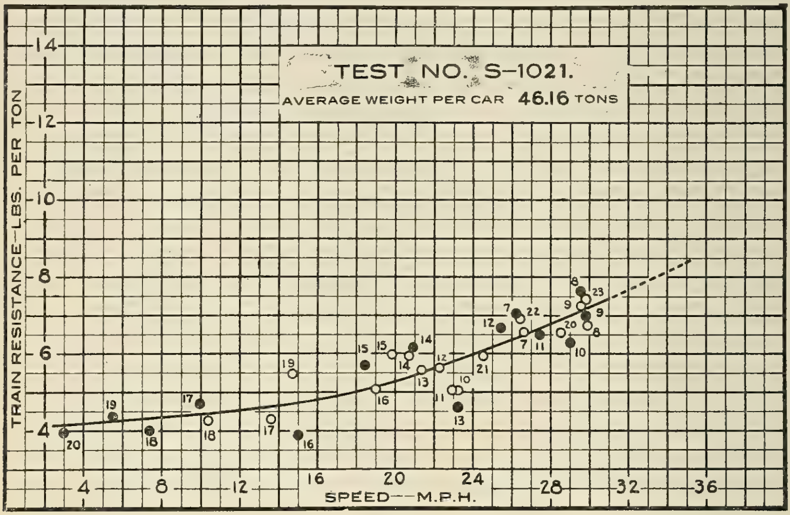

FIG. 1 THE RELATION OF RESISTANCE TO SPEED FOR TEST S-1021

The curve, such as is shown there, was next drawn to express, for the test in question, the relation existing between resistance and speed. In order to draw this curve, the plotted points were assumed to be arranged in a number of groups, and for each group the averages of the values of speed and of resistance were determined. By these averages a new point or "center of gravity" of the group was then plotted. The curve was drawn by confining attention to the few points thus determined. The groups of points were arbitrarily selected so that the resulting "centers of gravity" would be distributed nearly equidistantly throughout the speed range. All curves presented in the report, except those exhibited in Fig. 11, were drawn by this process.

All reasonable precautions have been taken to attain accuracy in the calculations. In determining each value of resistance, each step in the process was duplicated at a different time and generally by a different person. The transcription of all tables, the plotting of points and the drawing of curves have been similarly checked.

VI. THE RESULTS OF THE TESTS

18. *Results of the Individual Tests.*—The immediate result of each test is a curve which shows for the train under consideration the relation existing between train resistance and speed. Fig. 1 is such a curve derived from test S-1021; similar curves for the other tests are exhibited in Appendix 5. Fig. 1 is fairly representative of the entire group of curves, and such discussion of it as follows is general in its application.

The plotted points[1] show unmistakably an increase in resistance as the speed increases, and the curve drawn represents the mean relation between resistance and speed. In Fig. 1 the maximum variation from this mean of any calculated value of resistance is about 20 per cent; the next largest variation is 16 per cent and other calculated values of resistance differ from the values determined from the curve by generally less than 10 per cent. In a majority of the tests the maximum variation is less than in Fig. 1, and the general agreement between the calculated values of resistance and the ordinates of the curve is better than in the test chosen for illustration.

It has been thought desirable to express more specifically this variation between the calculated values of resistance and the mean values as derived from the curves drawn. To this end, for all tests, all calculated values of resistance for speeds between 8 and 12 miles per hour were compared with the ordinates of the curves at the corresponding speeds and the percentage difference was determined in each case. These percentages were then arranged in two groups and averaged. The one group included the results from all points lying above the curve, the other from those lying below it. The whole process was next repeated for speeds between 28 and 32 miles per hour. The results are as follows:—

AVERAGE DEVIATION (FOR ALL TESTS) OF CALCULATED RESISTANCE FROM THE MEAN VALUES DERIVED FROM THE CURVES—EXPRESSED IN PERCENTAGE OF THE MEAN VALUES.

Speed	Above the Mean	Below the Mean
8 to 12 m. p. h.	6.4 per cent	7.6 per cent
28 to 32 m. p. h.	5.6 per cent	6.6 per cent

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[1] The numbers shown near the points are the item numbers of the tables in Appendix 5. The tables exhibit the calculated values of resistance and speed, which are the co-ordinates of the plotted points.

Such variation seems not unduly great for this class of experimental work.

These differences may be due in part to accumulated errors in instruments or in the calculations. In all cases, however, where the calculated value of resistance varied by an unusual amount from the mean, all calculations leading thereto were repeated a second time and errors thus discovered have been eliminated from the report. The explanation for such differences need not be sought further than in the variations which actually occur from time to time, in the resistance itself. Variations in such components of train resistance as flange friction and wind resistance are probably sufficiently great to account for the differences discussed above. The data do not permit the influences of such components of resistance to be differentiated.

The curve drawn for each test has been accepted as representing the average values of net train resistance with a degree of accuracy sufficient for the purpose of rating locomotives. Such temporary excess of resistance as may be expected to occur will generally be absorbed in that reserve in the tractive effort of the locomotive which must be allowed in any system of tonnage rating.

19. *Results of All the Tests.*—The resistance curves for the individual tests have all been brought together on one sheet, a reproduction of which is shown as Fig. 2. The curves there drawn are duplicates of those separately shown in Appendix 5[1]. Fig. 2 displays the immediate results of the whole research. The lower curves give values of resistance varying from 3 lb. to 5½ lb. per ton, while the upper curves show resistance values varying from 7 lb. to 14 lb. per ton. Resistance values at the lower speeds differ by 100 per cent, and values at higher speeds differ by as much as 200 per cent. If further analysis had not revealed the cause of the great variation in resistance here shown, Fig. 2 would have remained a useless exhibit.

The explanation of this variation has been sought in the test conditions enumerated below, each of which, it was conceived, might have contributed in some degree to bring about the differences disclosed in Fig. 2:

(*a*) Weather and temperature conditions.

(*b*) Wind velocity and direction.

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[1] The numbers shown on the curves are the last two figures of the test numbers. The curve marked 43 is derived from test S–1043.

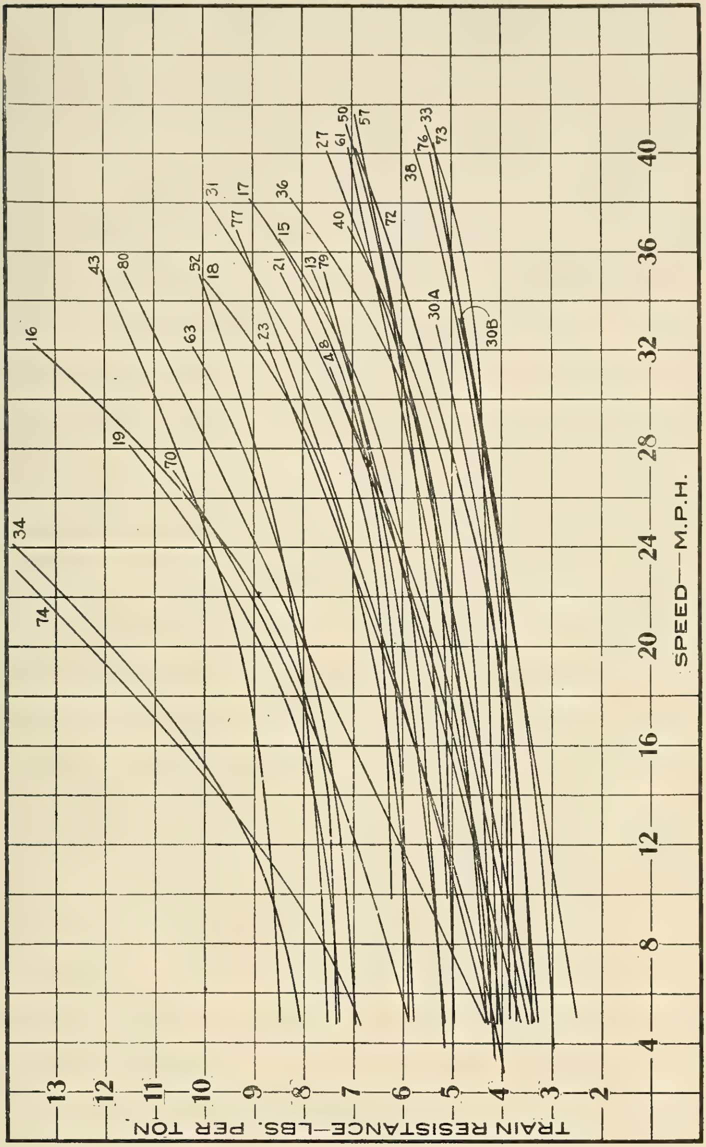

FIG. 2 CURVES SHOWING THE RELATION BETWEEN RESISTANCE AND SPEED FOR EACH OF THE TESTS

(*c*) Kind of cars composing the train.
(*d*) Position of the loaded cars in the train.
(*e*) Defects in train equipment.
(*f*) Average weight of the cars in the train.

The first five conditions are either uncontrollable or were purposely not controlled during these experiments. Attempts to explain the differences between the curves of Fig. 2 by reference to one or the other of these five factors have been altogether unsuccessful. While it is true that difference in wind velocity, for example, might be accepted as a plausible explanation of the differences between two or three curves selected at random from Fig. 2, such explanation will not hold when applied to two or three other curves similarly chosen; and it fails altogether to explain such differences when it is applied to the whole group. The same remarks apply to attempts to explain the differences between the curves of Fig. 2 by referring them to any other of the first five items cited above.

Item *f*, however, has furnished the clue whereby the apparent confusion in the results of the tests, as exhibited in Fig. 2, has been explained. It may be stated at once that the difference in train resistance for various tests is believed to be due chiefly to differences in the average gross car weights existing during the tests. An explanation of the process which led to this opinton follows immediately below. As was stated at the outset, this conclusion was anticipated when the work was begun, and the average car weight was therefore controlled during the experiments, and made to vary through the widest possible range.

20. *The Effects of Car Weight on Resistance.*—The four upper curves of Fig. 2 are derived from trains in which the average weight per car was about 16 or 17 tons. The lowest curves are those derived from trains in which the car weight was nearly 70 tons. These facts serve as a rough indication of the part played by car weight in effecting changes in train resistance. This influence is more definitely brought out in the following discussion.

If from each of the curves of Fig. 2 the value of resistance is determined at one speed, say 5 miles per hour, these values of resistance may then be plotted with respect to their corresponding values of car weight; and, since the speed is common, its influence is eliminated and the resulting diagram may be expected to reveal the relation existing between train resistance and average weight per car. Table 2 was prepared to facilitate this process. In it the tests are arranged in the order of the average car weights. These weights are given in the second column and in the succeeding columns are set down the resistance values obtained from the *curves* of the individual tests, for each of seven different speeds. Table 2 therefore presents the values of the coordinates of seven points on each of the curves of Fig. 2 and hence, like Fig. 2, summarizes the immediate results of all tests[1].

TABLE 2 VALUES OF RESISTANCE AT VARIOUS SPEEDS, DERIVED FROM THE CURVES FOR THE INDIVIDUAL TESTS. THIS TABLE PROVIDES THE CO-ORDINATES OF THE POINTS PLOTTED IN FIG. 3 TO 9.

Test No.	Aver. Weight per Car tons.	Train Resistance—pounds per ton.						
		5 m. p. h.	10 m. p. h.	15 m. p. h.	20 m. p. h.	25 m. p. h.	30 m. p. h.	35 m. p. h.
S-1016	16.12	7.35	7.40	7.62	8.37	9.91	12.22	
S-1034	16.56	8.10	8.70	9.92	11.90	14.30		
S-1074	16.56	6.92	8.23	10.10	12.32	14.70		
S-1043	16.92	8.50	8.61	8.85	9.30	10.00	10.95	12.04
S-1019	17.72	7.30	7.47	7.90	8.85	10.32		
S-1063	20.04	6.98	7.13	7.43	7.90	8.63	9.63	
S-1031	20.72		6.24	6.30	6.40	6.73	7.60	8.94
S-1080	21.40	4.40	5.57	6.75	7.94	9.15	10.35	11.55
S-1070	24.60	5.93	6.63	7.47	8.57	9.90		
S-1052	24.80	7.55	7.63	7.80	8.10	8.55	9.20	10.05
S-1018	25.40	5.80	5.95	6.20	6.63	7.22	8.26	10.02
S-1077	28.40	4.32	4.91	5.58	6.34	7.15	8.01	8.96
S-1079	33.04	3.66	4.30	4.92	5.60	6.22	6.89	7.55
S-1015	36.08	5.20	5.36	5.52	5.70	6.02	6.71	7.95
S-1036	37.72	4.98	5.03	5.12	5.15	5.31	5.88	7.15
S-1013	38.04		5.40	5.65	5.95	6.32	6.90	7.68
S-1017	38.44	5.90	5.95	6.02	6.20	6.48	7.01	8.03
S-1023	38.72	4.16	4.80	5.56	6.40	7.30	8.25	
S-1050	40.44		5.10	5.25	5.40	5.62	5.90	6.33
S-1057	41.32	3.40	3.88	4.35	4.83	5.31	5.80	6.30
S-1048	45.24	4.05	4.35	4.80	5.48	6.30	7.23	
S-1040	45.76	4.22	4.30	4.40	4.58	4.90	5.52	6.53
S-1021	46.16	4.21	4.41	4.72	5.29	6.15	7.20	8.40
S-1027	47.44	4.31	4.48	4.67	4.90	5.22	5.79	6.55
S-1061	51.20	3.50	4.00	4.51	5.01	5.51	6.01	6.53
S-1033	51.72	4.10	4.15	4.20	4.25	4.32	4.40	4.65
S-1038	52 28	3.30	3.50	3.71	3.95	4.25	4.60	5.08
S-1030B	57.12	3.73	3.80	3.82	3.90	4.10	4.50	
S-1030A	59.88	3.84	3.88	3.92	4.10	4.45	4.95	
S-1072	66.40	3.40	3.50	3.70	4.10	4.61	5.27	6.00
S-1073	67.16	2.52	2.90	3.30	3.70	4.10	4.50	4.90
S-1076	69.92	2.97	3.13	3.37	3.70	4.04	4.49	4.95

In Table 2 the second and third columns present a series of values of average car weight and of train resistance at 5 miles per hour. Each pair of these values represents the results of one of the 32 tests. Using these pairs of values as coordinates, a series of points has been plotted to form a new diagram, Fig. 3, For example, the point marked 21 in Fig. 3 is derived from the curve of test S-1021. The curve of resistance for this test (see Fig. 1 or Fig. 2) shows that at 5 miles per hour the mean resistance is 4.21 lb. per ton. During this test the average weight of the cars in the train was 46.16 tons. Table 2 also exhibits both of these values which, when plotted in Fig. 3, determine the point there marked 21. The other points of Fig. 3 were similarly determined. Each point represents the value of resistance at 5 miles per hour derived from a particular test train.

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[1] Table 2 has been prepared from the original curves of the individual tests, only one of which is separately presented in Part I (see Fig. 1). It gives no information not obtainable from Fig. 2, but presents the information in more convenient form, since the number of curves drawn in the figure makes it confusing.

Although there is considerable variation among the points of Fig. 3, they indicate clearly a decrease in the resistance as the car weight increases. The curve drawn in Fig. 3 represents, for the trains tested, the mean relation which existed between resistance at 5 miles per hour and the average car weight[1]. For higher speeds this relation between resistance and car weight is shown by Fig. 4 to 9, which were derived by the same methods employed in producing Fig. 3.

The variation in resistance represented by the points in Fig. 3 to 9 is sufficient to warrant further discussion. Such discussion will, however, be postponed until later in the report. The conclusion reached is that these variations are largely caused by factors which are uncontrollable in ordinary train operation. If this be admitted, it is clear that the discussion of such variations may enter into the solution of tonnage rating problems only as an argument for reserve tractive effort in the locomotive. An estimate of the desirable amount of such reserve appears beyond.

The curves of Fig. 3 to 9 have been accepted as representing, for these tests, the mean relation which existed between train resistance and the average gross weight of the cars composing the trains. These curves exhibit this relation at seven different speeds, 5, 10, 15, 20, 25, 30 and 35 miles per hour. For convenience in use and to make comparison easier, these seven curves have been brought together in one diagram which is reproduced in Fig. 10.

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[1] As has been previously explained, the curve is drawn by finding the "centers of gravity" of several groups of points These centers are defined in Fig. 3 to 9 by the crosses within circles. Points 34 and 74 were virtually ignored in drawing the curves of Fig. 6 and 7. The numbers at the points are the last two figures of the test numbers.

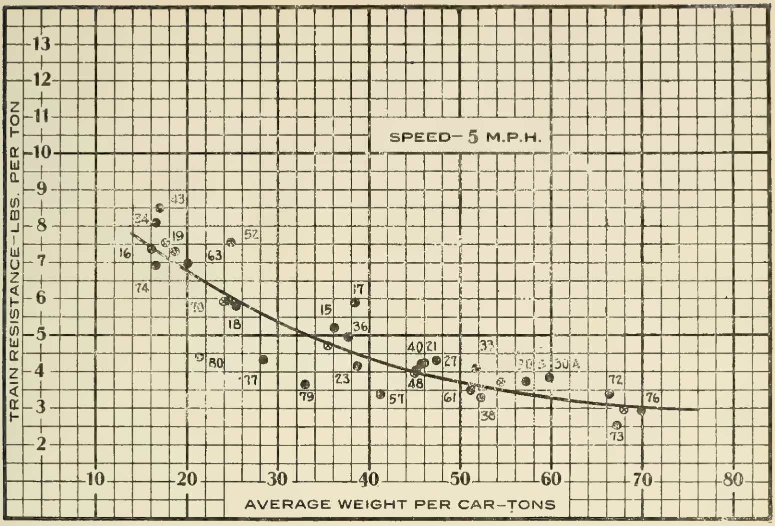

FIG. 3 THE RELATION BETWEEN RESISTANCE AND AVERAGE CAR WEIGHT, AT A SPEED OF 5 MILES PER HOUR

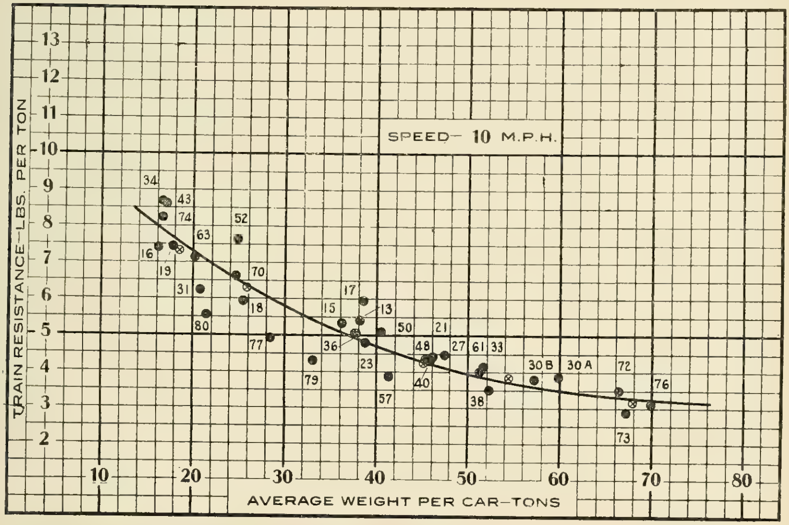

FIG. 4 THE RELATION BETWEEN RESISTANCE AND AVERAGE CAR WEIGHT, AT A SPEED OF 10 MILES PER HOUR

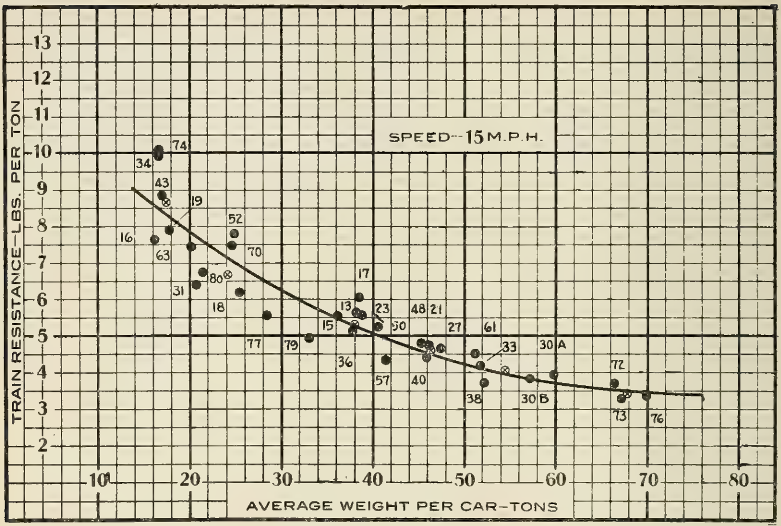

FIG. 5 THE RELATION BETWEEN RESISTANCE AND AVERAGE CAR WEIGHT, AT A SPEED OF 15 MILES PER HOUR

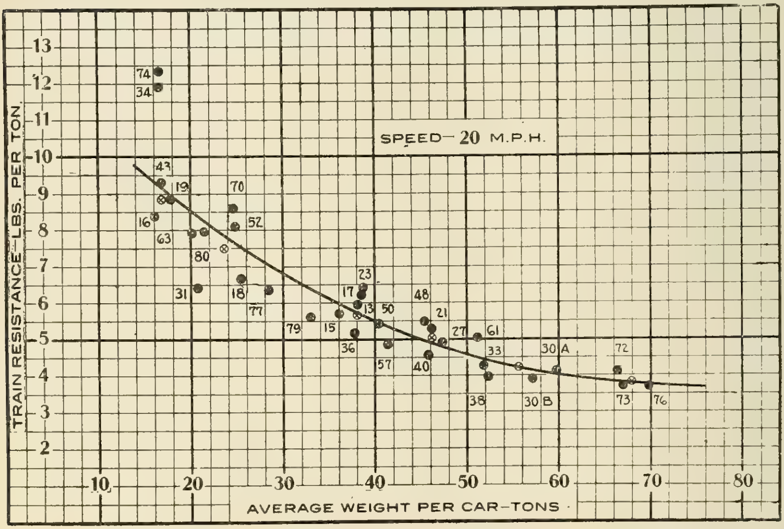

FIG. 6 THE RELATION BETWEEN RESISTANCE AND AVERAGE CAR WEIGHT, AT A SPEED OF 20 MILES PER HOUR

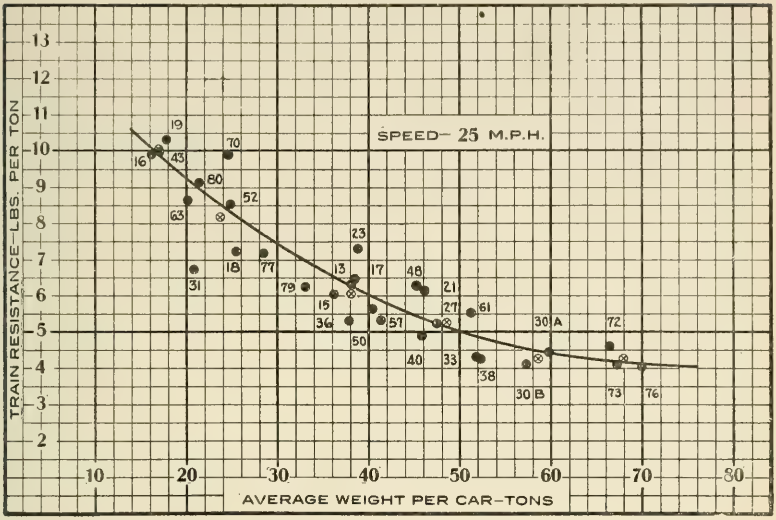

FIG. 7 THE RELATION BETWEEN RESISTANCE AND AVERAGE CAR WEIGHT, AT A SPEED OF 25 MILES PER HOUR

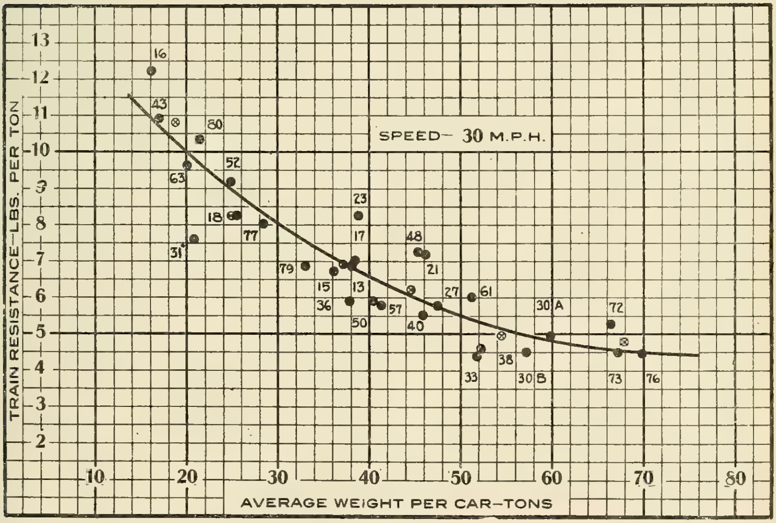

FIG. 8 THE RELATION BETWEEN RESISTANCE AND AVERAGE CAR WEIGHT, AT A SPEED OF 30 MILES PER HOUR

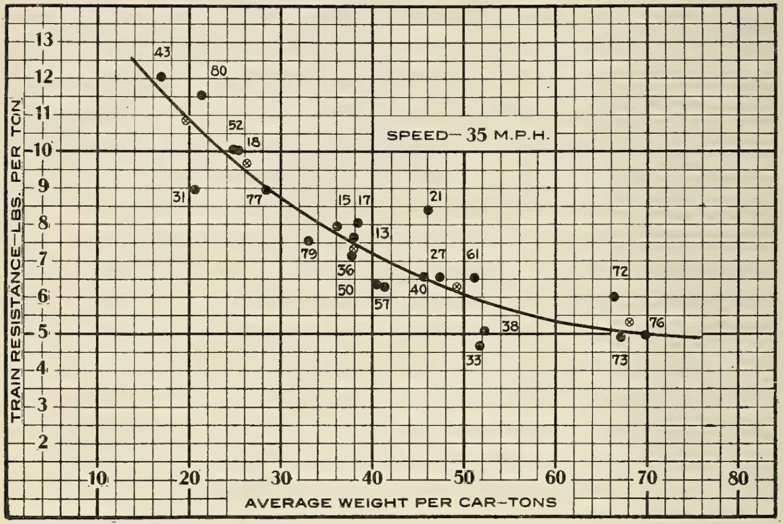

Fig 9 The Relation Between Resistance and Average Car Weight, at a Speed of 35 Miles per Hour

Fig. 10 presents the final results of the whole research. Each of the curves there drawn shows the mean relation, which existed during the tests, between car weight and resistance at a definite speed.

It is believed that the curves of Fig. 10 are generally applicable to ordinary American freight trains, provided the conditions surrounding their operation are like those which prevailed during these tests. The curves of Fig. 10 enable one to determine the probable mean resistance of any such train, at speeds between 5 and 35 miles per hour, provided the average weight of the cars composing the train be known.

21. *The Results Expressed as Resistance-Speed Curves.*—While Fig. 10 presents the main results of the experiments, the form in which these results are there expressed is unusual. Ordinarily, train resistance is expressed either as a curve or equation which defines the relation between resistance and speed, instead of the relation between resistance and car weight as in Fig. 10. Obviously, to express the results of these experiments in the usual form, a single curve will not suffice, since the influence of car weight cannot be thereby made evident. A number of curves will

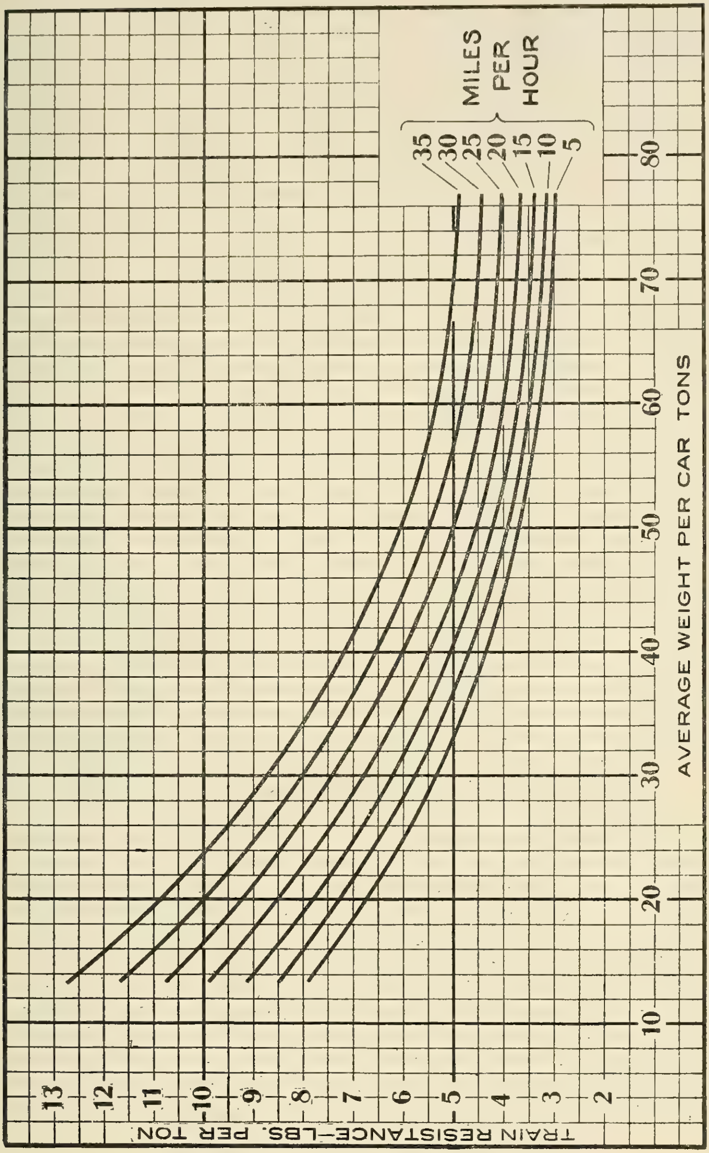

Fig. 10 The Relation Between Resistance and Average Car Weight, at Various Speeds

be required for this purpose each of which will apply only to a definite average car weight. Fig. 11 presents such a group of resistance-speed curves, which have been derived directly from the curves of Fig. 10. Fig. 11 therefore exhibits in different form only such information as is obtainable from Fig. 10.

The relation between the two figures may be made clear by explaining the derivation of the upper curve in Fig. 11,—the one applying to a car weight of 15 tons. In Fig. 10 the ordinate corresponding to an average car weight of 15 tons cuts the seven curves there drawn at 7 points, at which the mean resistance values are 7.62, 8.20, 8.81, 9.56, 10.37, 11.24 and 12.25 lb. per ton, corresponding to speeds of 5, 10, 15, 20, 25, 30 and 35 miles per hour, respectively. These values are the coordinates of 7 points on a resistance-speed curve applying to a car weight of 15 tons. These 7 points have been plotted in Fig. 11 and the upper curve there shown has been passed through them and extended to 40 miles per hour. The other curves of Fig. 11 were derived by a like process. In the original diagram three additional curves, corresponding to 55, 65, and 70 tons per car, were drawn. These three curves have been omitted from the figure to avoid confusion. Fig. 11 reproduces quite exactly the facts presented in Fig. 10[1]; and presents the final results of the experiments.

22. *The Results Expressed in Tabular Form.*—From each of the curves of Fig. 11 the values of resistance at various speeds have been determined and set down in Table 3. Table 3 also includes the coordinates of the resistance curves corresponding to 55, 65, and 70 tons per car, which are omitted from Fig. 11.

23. *The Results Expressed As Equations.*—The relation between resistance and speed shown by each of the curves of Fig. 11 may also be expressed in the form of an equation. Formulas 1 to 13 below are such equations, by means of which resistance may be calculated for any speed and for various car weights. In the formulas, R is the resistance expressed in pounds per ton, S is the speed expressed in miles per hour, and W is the average weight of the cars in the train expressed in tons. The formulas are purely empirical, and are simply equations of parabolas so

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[1] The points derived from Fig. 10 have been omitted from the tracing from which Fig. 11 was reproduced. All such points lie very close to the curves drawn in Fig. 11, the maximum deviation amounting to but ¾ of one per cent of the corresponding curve ordinate. In Appendix 6 there are presented tables of coordinates, by means of which Fig. 10 and 11 may be exactly reproduced.

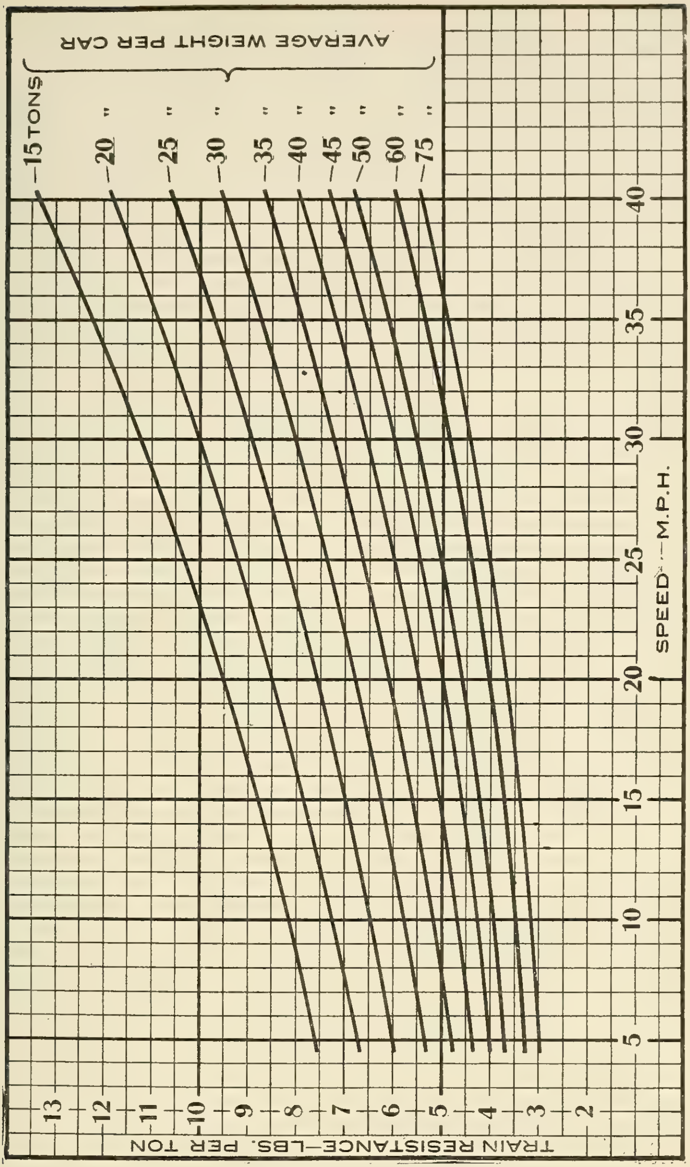

FIG. 11 THE RELATION BETWEEN RESISTANCE AND SPEED, FOR VARIOUS AVERAGE WEIGHTS PER CAR

selected as to correspond very closely with the curves of Fig. 11. The correspondence between the formulas and the curves is such that the maximum difference between any value of resistance obtained by the formulas and the corresponding value obtained from the curves of Fig. 11 is ½ of one per cent. Since these are empirical equations, their use should not be extended beyond the speed limits shown on Fig. 11.

TRAIN RESISTANCE FORMULAS.

When $W = 15$ tons; $R = 7.15 + 0.085\,S + 0.00175\,S^2$. (*1*)
When $W = 20$ tons; $R = 6.30 + 0.087\,S + 0.00126\,S^2$. (*2*)
When $W = 25$ tons; $R = 5.60 + 0.077\,S + 0.00116\,S^2$. (*3*)
When $W = 30$ tons; $R = 5.02 + 0.066\,S + 0.00116\,S^2$. (*4*)
When $W = 35$ tons; $R = 4.49 + 0.060\,S + 0.00108\,S^2$. (*5*)
When $W = 40$ tons; $R = 4.15 + 0.041\,S + 0.00134\,S^2$. (*6*)
When $W = 45$ tons; $R = 3.82 + 0.031\,S + 0.00140\,S^2$. (*7*)
When $W = 50$ tons; $R = 3.56 + 0.024\,S + 0.00140\,S^2$. (*8*)
When $W = 55$ tons; $R = 3.38 + 0.016\,S + 0.00142\,S^2$. (*9*)
When $W = 60$ tons; $R = 3.19 + 0.016\,S + 0.00132\,S^2$. (*10*)
When $W = 65$ tons; $R = 3{\cdot}06 + 0.014\,S + 0.00130\,S^2$. (*11*)
When $W = 70$ tons; $R = 2.92 + 0.021\,S + 0.00111\,S^2$. (*12*)
When $W = 75$ tons; $R = 2.87 + 0.019\,S + 0.00113\,S^2$. (*13*)

The results of the tests may also be approximately expressed by the following single empirical equation in which R is expressed in terms of both S and W.

$$R = \frac{S + 39.6 - 0.031\,W}{4.08 + 0.152\,W} \cdots\cdots\cdots\cdots (14).$$

When compared with the results of the tests as shown in Figure 11, or in Table 69 in Appendix 6, this equation results in a maximum error of 9.5 per cent. This error occurs when $S = 21$ and $W = 55$. For all other values of S and W the error resulting from the use of the equation is 9.0 per cent or less.

24. *Final Results.*—The final results of the research are presented in Fig. 11, in Table 3, and in formulas 1 to 13. It is believed that by means of the figure, or the table or the formulas, the resistance of ordinary freight trains may be fairly accurately predicted; provided the conditions surrounding their operation are similar to those which prevailed during these tests. These conditions have been fully stated and are restated in the conclusions.

It is sufficient to repeat at this point that the results apply to trains running at uniform speed, on tangent and level track of good construction, during weather when the temperature is not lower than 30° F., and when the wind velocity does not exceed about 20 miles per hour.

TABLE 3

VALUES OF RESISTANCE AT VARIOUS SPEEDS AND FOR TRAINS OF DIFFERENT AVERAGE WEIGHTS PER CAR.

The values are derived directly from the curves of Fig. 11 and represent the final results of the tests.

Speed miles per hour	Train Resistance—Pounds per ton													Speed miles per hour
	Column Headings Indicate the Average Weights Per Car													
	15 tons	**20** tons	**25** tons	**30** tons	**35** tons	**40** tons	**45** tons	**50** tons	**55** tons	**60** tons	**65** tons	**70** tons	**75** tons	
5	7.6	6.8	6.0	5.4	4.8	4.4	4.0	3.7	3.5	3.3	3.2	3.1	3.0	5
6	7.7	6.9	6.1	5.5	4.9	4.4	4.1	3.8	3.5	3.3	3.2	3.1	3.0	6
7	7.8	7.0	6.2	5.5	5.0	4.5	4.1	3.8	3.6	3.4	3.2	3.1	3.1	7
8	8.0	7.1	6.3	5.6	5.0	4.6	4.2	3.9	3.6	3.4	3.3	3.2	3.1	8
9	8.1	7.2	6.4	5.7	5.1	4.6	4.2	3.9	3.6	3.4	3.3	3.2	3.1	9
10	8.2	7.3	6.5	5.8	5.2	4.7	4.3	4.0	3.7	3.5	3.3	3.2	3.2	10
11	8.3	7.4	6.6	5.9	5.3	4.8	4.3	4.0	3.7	3.5	3.4	3.3	3.2	11
12	8.4	7.5	6.7	6.0	5.4	4.8	4.4	4.0	3.8	3.6	3.4	3.3	3.3	12
13	8.6	7.6	6.8	6.1	5.5	4.9	4.5	4.1	3.8	3.6	3.5	3.4	3.3	13
14	8.7	7.8	6.9	6.2	5.5	5.0	4.5	4.2	3.9	3.7	3.5	3.4	3.4	14
15	8.8	7.9	7.0	6.3	5.6	5.1	4.6	4.2	3.9	3.7	3.6	3.5	3.4	15
16	9.0	8.0	7.1	6.4	5.7	5.1	4.7	4.3	4.0	3.8	3.6	3.5	3.5	16
17	9.1	8.1	7.2	6.5	5.8	5.2	4.8	4.4	4.1	3.9	3.7	3.6	3.5	17
18	9.3	8.3	7.4	6.6	5.9	5.3	4.8	4.5	4.1	3.9	3.7	3.7	3.6	18
19	9.4	8.4	7.5	6.7	6.0	5.4	4.9	4.5	4.2	4.0	3.8	3.7	3.6	19
20	9.6	8.5	7.6	6.8	6.1	5.5	5.0	4.6	4.3	4.0	3.9	3.8	3.7	20
21	9.7	8.7	7.7	6.9	6.2	5.6	5.1	4.7	4.3	4.1	3.9	3.9	3.8	21
22	9.9	8.8	7.9	7.0	6.3	5.7	5.2	4.8	4.4	4.2	4.0	3.9	3.8	22
23	10,0	9.0	8.0	7.1	6.4	5.8	5.3	4.9	4.5	4.3	4.1	4.0	3.9	23
24	10.2	9.1	8.1	7.3	6.6	5.9	5.4	4,9	4.6	4.3	4.2	4.1	4.0	24
25	10.4	9.3	8.3	7.4	6.7	6.0	5.5	5.0	4.7	4.4	4.2	4.1	4.0	25
26	10.5	9.4	8.4	7.5	6.8	6.1	5.6	5.1	4.8	4.5	4.3	4.2	4.1	26
27	10.7	9.6	8.5	7.7	6.9	6.2	5.7	5.2	4.8	4.6	4.4	4.3	4.2	27
28	10.9	9.7	8.7	7.8	7.0	6.3	5.8	5.3	4.9	4.7	4.5	4.4	4.3	28
29	11.1	9.9	8.8	7.9	7.1	6.5	5.9	5.4	5,0	4.8	4.6	4.5	4.4	29
30	11.3	10.0	9.0	8.0	7.3	6.6	6.0	5.5	5.1	4.9	4.7	4.5	4.5	30
31	11.4	10.2	9.1	8.2	7.4	6.7	6.1	5.6	5.2	5.0	4.8	4.6	4.5	31
32	11.6	10.4	9.3	8.3	7.5	6.8	6.2	5.8	5.3	5.0	4.9	4.7	4.6	32
33	11.8	10.5	9.4	8.5	7.6	7.0	6.3	5.9	5.4	5.2	5.0	4.8	4.7	33
34	12.0	10.7	9.6	8.6	7.8	7.1	6.5	6.0	5.5	5.3	5.1	4.9	4.8	34
35	12.3	10.9	9.7	8.8	7.9	7.2	6.6	6.1	5.7	5.4	5.2	5.0	4.9	35
36	12.5	11.1	9.9	8.9	8.0	7.4	6.7	6.2	5.8	5.5	5.3	5.1	5.0	36
37	12.7	11.2	10.0	9.0	8.2	7.5	6.9	6.4	5.9	5.6	5,4	5.2	5.1	37
38	12.9	11.4	10.2	9.2	8.3	7.6	7.0	6.5	6.0	5.7	5.5	5.3	5.2	38
39	13.1	11.6	10.4	9.4	8,5	7,8	7.1	6.6	6,2	5.8	5.6	5.4	5.3	39
40	13.4	11.8	10.6	9.5	8.6	7.9	7.3	6.8	6.3	6.0	5.7	5.6	5.5	40

VII. DISCUSSION OF THE RESULTS

25. *Variation in Resistance of Different Trains*.—Reference has been made to the variations among the points of Fig. 3 to 9. In

each figure about one half of the points lie above the curve there drawn, and their resistance values vary from those of the curve by different amounts. It should be borne in mind that, in these figures, each point represents the average resistance which prevailed throughout a particular test, and differences among the points represent, therefore, differences in the mean resistance of the different trains.

Among those trains which are regarded as normal there are two or three whose resistance at some speed varies from the mean, as expressed in the curves, by as much as 23 per cent. The great majority, however, vary from this mean by about 10 per cent or less. In Fig. 4, for example, there are 19 points which lie above the curve, among which the maximum deviation from the mean is 23 per cent, while the average of the deviations for all 19 points is 8 per cent. The following table presents similar average deviations above and below the mean for each of Fig. 3 to 9.

Average Deviation of All Points in Fig. 3 to 9, from the Mean as Shown by the Curves There Drawn.—Expressed as Percentages of the Curve Ordinates.

	Fig. 3 5 m. p. h.	Fig. 4 10 m. p. h.	Fig. 5 15 m. p. h.	Fig. 6 20 m. p. h.	Fig. 7 25 m. p. h.	Fig. 8 30 m. p. h.	Fig. 9 35 m. p. h.
Points above the curve	11	8	8	11	13	8	7
Points below the curve	13	10	9	8	9	9	9

The data present no satisfactory general explanation for these differences in the resistance of different trains of like average weight per car. They may be due to difference in external conditions or to difference in train condition and make-up. Whatever may be the explanation for these differences it is significant that about one-half of the trains experimented upon developed a resistance about 9 per cent in excess of the mean resistance which would be predicted by the use of Fig. 3 to 9 and Fig. 10 and 11. Obviously a similar excess may be expected with any train, and it is suggested therefore that, in determining the resistance of trains on *level tangent track* for the purpose of rating locomotives under operating conditions which demand conservative ratings, 9 per cent be added to the resistance values obtained from the curves, tables, and equations presented. Such considerations are of little practical importance in rating locomotives for speeds above 15 miles per hour. In such cases an excess in resistance over that expected can result in nothing more serious than failure to realize the expected train speed.

It should be understood that this 9 per cent allowance is intended to cover probable variations in the resistance of different trains under normal operating conditions. It in no way takes the place of that additional reserve which must be allowed to cover unusual variations in resistance due to low temperatures or high winds, or of that reserve in tractive effort of the locomotive which is necessitated by operating conditions which reduce the efficiency of the locomotive itself.

26. *Tests Which Present Abnormal Resistance Values.*—There are four points in Fig. 3 to 9 whose deviation from the curves is so great as to demand special examination. These are the points corresponding to tests S–1034, S–1074, S–1080, and S–1031 (points 34, 74, 80, and 31). These tests show a persistent and great variation from the mean at various speeds. The trains of tests 1034, 1074, and 1080 were alike in having average car weights less than 23 tons and in containing a large proportion of empty gondolas, 99, 98, and 84 per cent, respectively. Any explanation based on the train composition is however nullified by the fact that the trains of tests No. 1016, 1043, and 1063, which show close correspondence with the curves, had similar average car weights and contained almost equally large proportions of empty gondolas. Weather and wind conditions likewise offer no explanation of the divergences presented by these three tests. Explanations are rendered more difficult by the fact that, while the trains of tests 1034 and 1074 show unusually high resistance, the resistance in test 1080 is exceptionally low. The abnormalities presented by these three trains have therefore been accepted as unexplained by the data at hand.

The resistance of the trains of the fourth test mentioned above (S–1031) is low at all speeds. This train had an average car weight of 20.7 tons, contained 94 per cent of box cars, and was only 1425 ft. long. Other test trains of similar average car weight differ from this in having generally less than 60 per cent of box cars and in being all 2400 ft. or more in length. Taking into consideration all the data, neither fact seems, however, to offer an adequate explanation of the variations exhibited by this train.

27. *Car Weight as a Basis of Expression.*—Objection may be made to the form of expression adopted in Fig. 3 to 9 and 10, in which the resistance is expressed solely in terms of average car weight, to the apparent neglect of the influence of those elements of resistance, such as air resistance, which are independent of weight and which probably vary only with the number of cars in the train. The neglect is only apparent, however, for the process by which Fig. 10 was derived involves, although indirectly, the recognition of the influence of the number of cars. It is quite likely that, if Fig. 10 were applied to determine the total resistance of a single car, the result would be in error.

Whatever objection may be urged against the form of expression adopted, it remains true that Fig. 10 rests upon experimental results obtained with trains of usual length and that in practice one is not likely to encounter trains which present in this respect any extreme variation from the test data. The form of expression will not lead to error unless misapplied and it was chosen because it permits the results to be conveniently used in establishing tonnage ratings.

It might likewise have been more rational to express the resistance in terms of load per axle instead of load per car, since the latter can operate to cause variations in resistance only in so far as it affects the former. Since, however, all American freight cars have four axles, the expression in either form would be identical. Convenience in application warrants the choice made in this respect also.

28. *Effect of Variety in Car Weight upon Total Train Resistance.*—In Fig. 10 those portions of the curves which apply to average car weights below 20 tons were derived from trains which were quite homogeneous in their make-up as regards weight per car. These trains were necessarily composed almost exclusively of empty cars, since an average car weight of 20 tons or less cannot be obtained with cars of current design unless they are empty or nearly so, and being empty they will be uniform in weight. Similarly for average car weights above 55 or 60 tons, the test trains were necessarily uniform in make-up. For trains of average car weights below 20 and above 60 tons, the curves of Fig. 10 are ac-

cepted, therefore, as valid and applicable to any train to be met with in practice.

In Fig. 10, those portions of the curves corresponding to car weights of from 20 to 60 tons were, on the other hand, derived from trains which presented considerable diversity in make-up as regards weight per car. Some of these trains were composed almost entirely of loaded cars, others contained large proportions of both empty and loaded cars. In presenting the results in the form adopted in Fig. 10 (and Fig. 11) the assumption is that the curves there drawn will be used throughout their entire range of average car weight to determine the total resistance of both homogenous and mixed trains, and that, when so applied, they will lead to no material error. In view of the facts just stated it is pertinent to inquire whether this assumption is justifiable.

Assume two trains of equal tonnage, and of the same average weight per car. Assume further that one is composed of cars uniform in weight, and that the other is composed of cars of different individual weights. Now if such trains are to have equal total resistance, it can be shown that the variation in the resistance *per car* of the individual cars must be directly proportional to their weight. This implies that the curve showing the relation between *total car resistance* and car weight at a given speed must be a straight line, if homogeneous and mixed trains are to have equal total resistances at this speed. From Fig. 10 there have been derived curves showing this relation between car resistance and car weight. These curves (not shown in the report) correspond quite closely, but not exactly, with straight lines; and the correspondence is especially close for those portions of the curves which apply to car weights between 20 and 60 tons. From these facts we may conclude that the curves of Fig. 10 are not quite, but are nearly equally applicable to mixed and homogeneous trains, and that, if the curves are applied to both kinds of trains, we may expect a slight error in the resulting total train resistance. The amount of such error is indicated by the following examination of a specific case.

Assume two trains, A and B, the first homogeneous, the second mixed, as regards car weight. Train A is composed of 60 cars, each weighing 45 tons, and its total weight is 2700 tons. Train B is composed of 30 cars of 70 tons each, and 30 cars of 20 tons each; its total weight is 2700 tons and its average car weight is 45 tons. Train B presents about as great a diversity in car weight as may be encountered in current practice. Both trains have equal tonnage and the same average weight per car. Assume that the total resistance of these two trains at a speed of 5 miles per hour is to be determined. By the procedure, which it is intended shall usually be followed in using Fig. 10, the resistance for an average car weight of 45 tons, at 5 miles per hour, is found to be 4.0 lb. per ton; and the total resistance of either train A or train B is 2700 x 4.0 =10 800 lb.

Train B, however, may be considered as made up of two shorter homogeneous trains of average car weights of 20 and 70 tons respectively and the resistance of each may be determined from those portions of the curves of Fig. 10, about whose validity no question is raised. From Fig. 10, the resistance at 5 miles per hour for a car weight of 20 tons is found to be 6.8 lb. per ton and for a car weight of 70 tons, 3.1 lb. per ton. By the use, therefore, of these portions of the curves of Fig. 10, the total resistance of train B is found to be 30 x 20 x 6.8 + 30 x 70 x 3.1 = 10 590 lb., which differs from the resistance previously found by 2 per cent. If a similar analysis be made for a speed of 40 miles per hour, the corresponding difference is found to be 4 per cent. If these differences be accepted as a measure of the maximum error likely to result from the indiscriminate application of the curves of Fig. 10 to mixed and homogeneous trains, we may conclude that for purposes of rating locomotives the results of the tests as expressed in Fig. 10 and 11 and Table 3 may be so applied without material error.

29. *The Influence of Speed on Resistance.*—Within the last two years the opinion has been expressed in some quarters that train resistance between speeds of 5 and 35 miles per hour is constant. It is proper to point out that there is nothing in the data here presented to support such a conclusion.

30. *The Influence of Wind Velocity on Resistance.*—The wind velocities prevailing during the tests were generally less than 20 miles per hour. The data do not permit the influence of such winds to be differentiated from the other elements affecting resistance; but they do warrant the conclusion that this influence is small. In the introduction, train resistance was defined as the

resistance in still air, whereas throughout the report the term is used to apply to the test results from which the influence of wind has not been eliminated. This inconsistency has been deliberately incurred to avoid unwieldy expression and is partially justified by the facts just stated.

31. *Comparison with Other Experiments.*—There is no point in comparing the results of these tests with formulas in which the influence of car weight is given no consideration, nor with those which are not derived from tests with American cars of recent design. The results obtained on the Chicago, Burlington and Quincy Railroad and on the Pennsylvania Railroad, and recently published by Mr. F. J. Cole,[1] take into consideration the influence of car weight and they apply to cars of recent design. They are therefore selected for comparison.

The results obtained on the Chicago, Burlington and Quincy road (curve No. 1, for temperatures above 30° F. and no wind) apply to a speed of 20 miles per hour. Compared with the curve for 20 miles per hour in Fig. 10, they show resistance values which are from 35 to 60 per cent lower than the corresponding results of these tests. The Pennsylvania Railroad results are claimed to be equally applicable at all speeds between 5 and 30 miles. When plotted on Fig. 10 of this report they show very close correspondence with the curve there drawn for 10 miles per hour, for car weights from 25 to 70 tons; while for car weights below 25 tons they indicate resistance values as much as 20 per cent in excess of the results obtained during these tests.

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[1] Railway Age Gazette, August 27 to October 1, 1909.

APPENDIX 1

APPENDIX 1

RAILWAY TEST CAR NO. 17

The dynamometer car by means of which these tests were made was built in 1900. Under the arrangements perfected at that time, the car was built and has since been maintained by the Illinois Central Railroad, while the University has supplied all apparatus, and has manned and operated the car. Both the car body and the apparatus were remodeled in 1907[1].

The car body was especially designed for its purpose. It is 40 ft. long over the end sills, and 8 ft. 4 in. wide inside. The central sills and the platforms are of steel, while the remainder of the construction is of wood. The general design of the car is shown in Fig. 12, and an interior view is shown in Fig. 13. The working space occupies about two thirds of the length of the car, and in it are placed the recording apparatus, the auxiliary instruments, the storage batteries, work-bench, etc.

During the tests, the test car apparatus made continuous autographic records of drawbar pull, speed, time, mile post positions, airbrake cylinder pressure, wind velocity with respect to the car, and wind direction with respect to the longitudinal axis of the car. These records are made upon a chart 36 in. wide, drawn across the table of the recording apparatus. This chart was driven by gearing from the axle of the central truck below the car, so that its travel was proportional to the travel of the car itself. In all tests a car travel of one mile produced a paper travel of 13.2 in. A view of the recording apparatus is shown in Fig. 14.

Fig. 15 is reproduced from a tracing of a portion of the chart made during test S-1057 of this series. The only lines there shown which do not appear on the original record are the profile and the transverse lines which mark the limits of one of the sections selected for calculation. These lines and some of the explanatory lettering have been added to the tracing, in order to make clearer the significance of the various records.

The total pull which comes upon the measuring drawbar of the car is transmitted to oil contained in the receiving cylinder, the design of which is shown in Fig. 16. This cylinder is hung

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[1] A more detailed description of the present equipment is contained in an article by F. W. Marquis, in the Railway Age Gazette February 19, 1909.

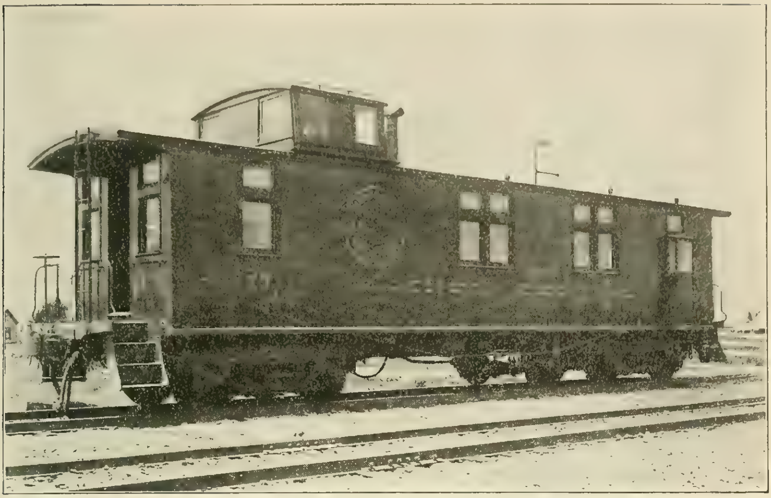

FIG. 12 RAILWAY TEST CAR NO. 17

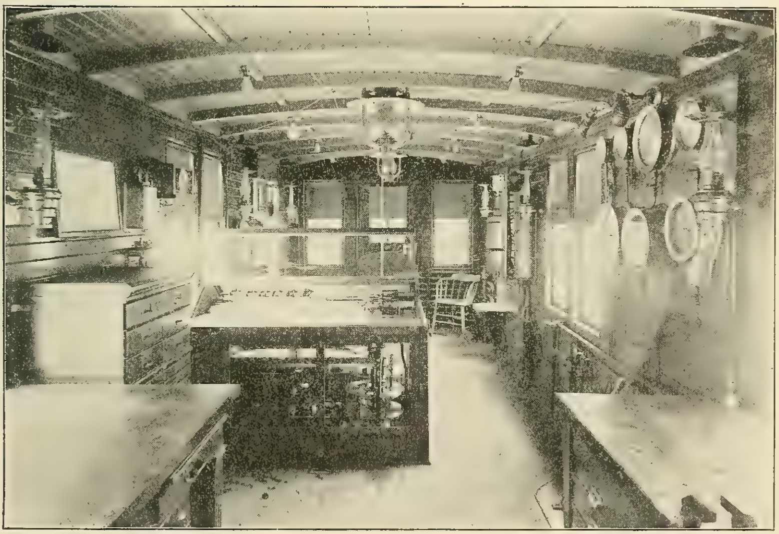

FIG. 13 INTERIOR OF TEST CAR NO. 17

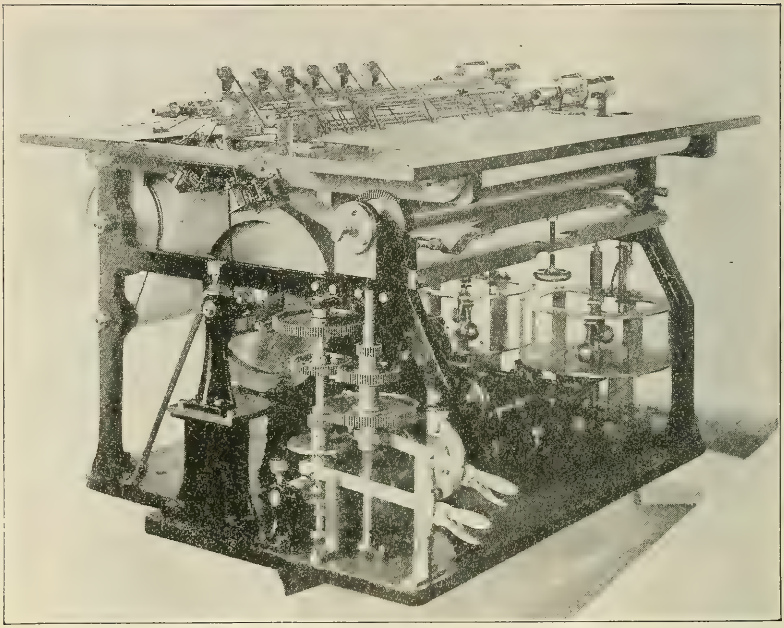

FIG. 14 THE RECORDING APPARATUS

from the center sills, immediately behind the drawbar yoke. Its inside diameter is 10 in., and its piston is 7½ in. long. Both cylinder and piston are carefully ground to an exact fit and no piston packing is used. The pull is transmitted from the drawbar yoke to the piston through a roller-borne yoke; and the whole device is practically frictionless. Such leakage of oil as takes place proceeds so slowly as to prove no inconvenience, even when operating under maximum pull. The cylinder may be refilled with oil by means of a pump within the car, and this is done while the car is in operation and without impairing the accuracy of the record. The pressure of the oil in this receiving cylinder is transmitted to the cylinder of an indicator located upon the table within the car. This indicator is identical, in its design, with one of the modern types of steam engine indicators, although it is larger and heavier throughout. During its ten years of service this type of dynamometer has demonstrated its reliability and accuracy.

Two speed records are shown on the chart, and both are used. The one is obtained from a speed recorder which resembles in design a "fly-ball" engine governor. This instrument is used in measuring speeds above 15 miles per hour. The second record is obtained from a chain-driven Boyer speed recorder, geared to run at a speed about three times as great as is usual with these instruments. This record is used for speeds up to 35 miles per hour. Within their respective ranges, both instruments produce accurate speed curves.

The air-brake cylinder of the test car is connected to the cylinder of an ordinary steam engine indicator, which is mounted upon the table and which draws a curve of air-brake cylinder pressure.

The velocity of the wind with respect to the car is obtained by means of a Robinson cup-anemometer of the standard United States Weather Bureau type, which is so mounted that the cups revolve 32 in. above the car roof. This instrument controls an electric circuit, which operates an electro-magnet connected to the recording pen. By means of this magnet offsets are made in the line drawn by the pen. During the time which elapses between two successive offsets, the travel of the air past the cups amounts to 0.2 of a mile.

The direction of the wind with respect to the longitudinal axis of the car is derived from a wind vane mounted 3 ft. above the car roof. The spindle of the vane extends downward to a point above the recording apparatus and terminates there in a crank, parallel to the vane. This crank is connected to the recording pen through a rod with a yoke end. The ordinate of the curve drawn by this pen is proportional to the sine of the angle made by the vane with the car axis. The offsets in the datum line for this curve, which appear in Fig. 15, indicate that the vane, at the moment, was pointed toward the front end of the car. While the vane points toward the rear end no offsets are made in the datum line.

Fig. 15 shows a record of "area under the curve of pull" which is made by means of a recording planimeter mounted on the table. This record is inaccurate and was not used in these calculations.

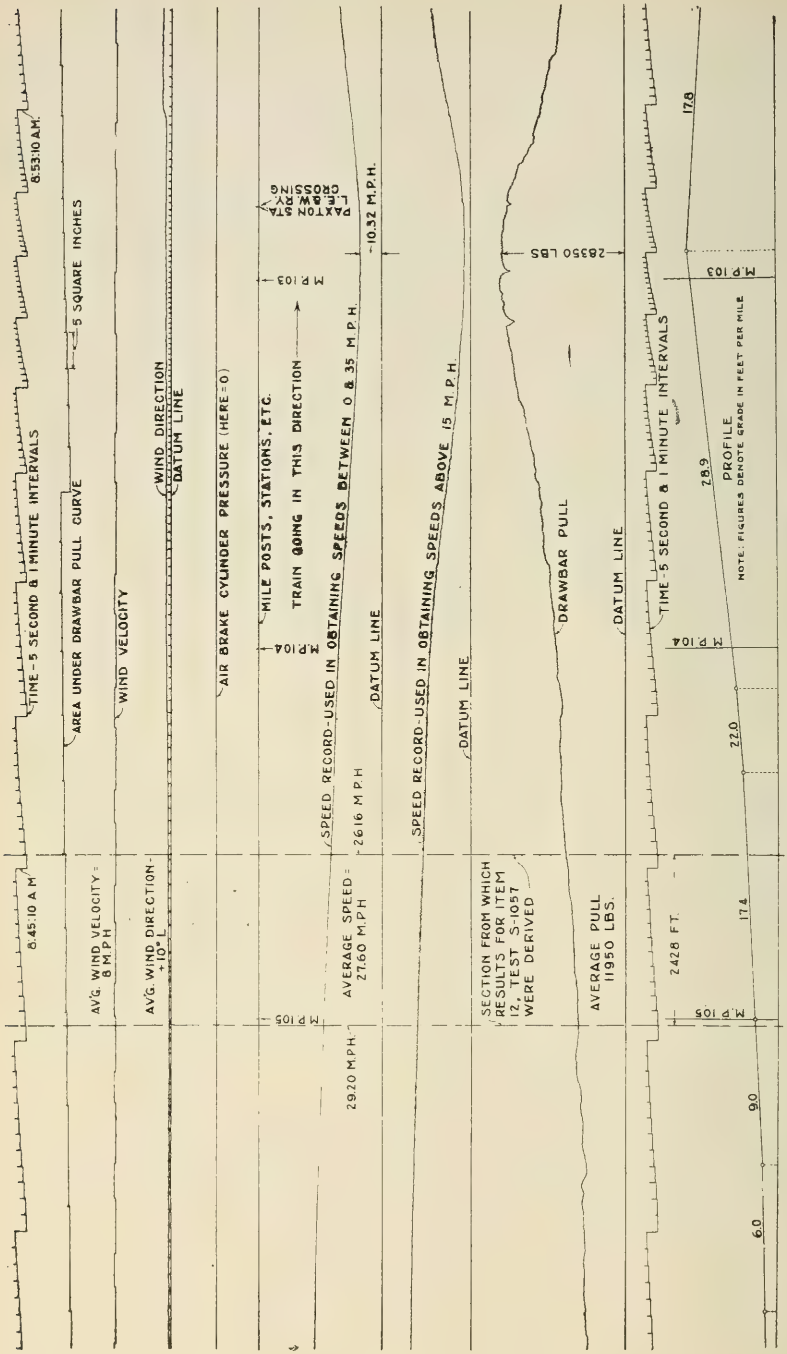

FIG. 15 A PORTION OF THE CHART FROM TEST S-1057

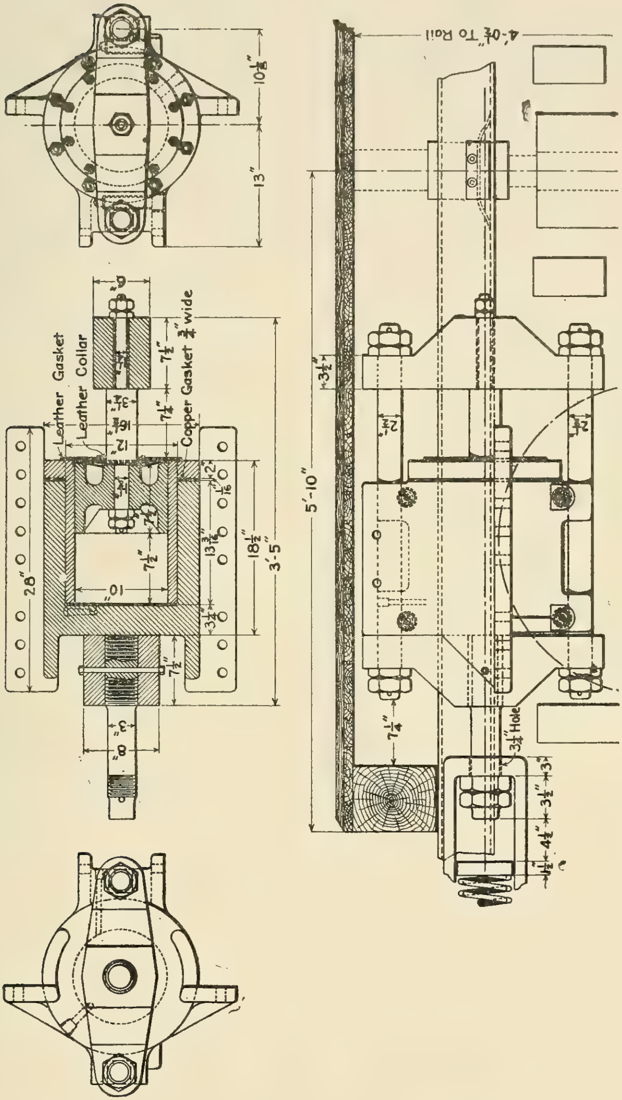

FIG. 16 THE RECEIVING CYLINDER OF THE DYNAMOMETER

APPENDIX 2

APPENDIX 2

THE TONNAGE RECORDS OF THE TRAINS

Tables 4 to 35 present the records of make-up and tonnage of the trains. The car numbers are arranged in the tables in the order in which the cars were placed in the train, beginning at the head end.

With the few exceptions cited in Part I, the weights given in the last column of the tables were obtained by weighing the train on the track scales. In all tests the dynamometer car was coupled immediately behind the locomotive tender. In the tonnage records for those tests in which the test car ran with its measuring drawbar pointed toward the rear of the train, the test car weight is excluded, since in such cases its own resistance is not included in the pull recorded on the chart.

TABLE 4 Tonnage Record

Test No. S-1013

Kind of Car	Loaded or Empty	Car No.	Car Initial	Stenciled Light Weight	Capacity	Gross Weight
	L or E			pounds	pounds	pounds
Test Car	E			58 000		58 000
Gondola	L	82 386	I. C.	28 700	60 000	92 300
Refrigerator	E	6 641	N. C. L.		60 000	36 400
Box	L	48 887	I. C.	39 100	80 000	96 200
"	"	36 476	"	37 000	80 000	92 000
"	"	92 329	N. C. & St. L.	33 300	60 000	95 000
"	"	9 842	N. C. & St. L.	33 400	60 000	94 000
"	"	37 668	I. C.	34 600	80 000	107 000
"	"	14 301	"	29 200	60 000	72 700
Refrigerator	E	726	C. B. T.			38 200
Box	L	38 254	I. C.	34 000	80 000	58 700
Gondola	"	85 604	"	31 500	80 000	105 100
Box	"	39 840	"	38 900	80 000	82 400
"	"	9 337	L. & N.	34 500	65 000	69 300
"	"	94 116	"	35 400	65 000	64 700
"	"	3 135	"	34 000	65 000	89 600
Refrigerator	E	5 260	A. R. L.	36 500	50 000	38 100
Box	L	39 404	I. C.	38 300	60 000	122 000
Gondola	E	16 778	Erie	42 800	100 000	42 600
Box	L	38 711	I. C.	37 600	80 000	86 500
"	"	5 078	N. C. & St. L.	38 300	60 000	76 000
"	"	3 954	L. & N.	33 100	65 000	94 000
"	"	133 684	S. O.	33 200	60 000	68 000
Gondola	"	3 193	I. S.	40 200	100 000	147 800
Tank	"	704	B. T. R.			78 500
"	"	540	D. R. & U.			80 000
"	"	293	A. C. O.			88 100
Gondola	"	82 968	I. C.	28 400	60 000	83 700
Box	"	34 623	"	37 100	60 000	68 100
"	"	19 773	"	28 300	60 000	62 600
"	"	47 730	"	30 600	80 000	108 700
"	"	130 091	"	42 300	80 000	88 100
"	"	14 834	"	31 600	60 000	74 000
Refrigerator	"	5 223	M. R. T.			50 600
Box	"	48 273	I. C.	39 700	80 000	99 600
"	"	36 741	"	34 500	80 000	119 200
"	"	36 076	"	35 700	80 000	122 000
"	"	49 417	"	35 200	80 000	90 000
"	"	34 147	"	37 000	80 000	92 300
"	"	136 690	S. O.	34 300	60 000	87 800
"	"	32 645	"	31 800	60 000	36 600
"	"	17 853	I. C.	29 900	60 000	63 900
"	"	45 691	"	39 400	80 000	100 000
"	"	38 217	"	34 000	80 000	74 300
Gondola	"	93 582	"	30 400	80 000	115 600
Box	"	47 588	"	41 600	80 000	89 300
"	"	140 760	"	42 900	100 000	76 000
"	"	45 432	"	36 300	80 000	123 300
"	"	12 104	"	28 800	60 000	64 300
"	"	22 796	"	37 500	80 000	113 600
"	L	48 388	"	39 700	80 000	63 500
"	E	22 742	L. S. & M. S.	29 300	60 000	31 000
"	L	36 825	I. C.	33 900	80 000	72 000
Gondola	"	79 267	"	24 800	50 000	27 000
Box	"	12 784	"	28 300	60 000	63 000
Gondola	"	81 750	"	26 700	60 000	65 500
Refrigerator	E	275	B. T.	28 000	60 000	32 000
Box	"	11 972	W. C.	29 900	60 000	29 300
"	L	12 658	I. C.	37 400	80 000	63 000
"	E	45 051	"	36 000	60 000	67 000
"	L	20 070	"	28 500	60 000	84 000
"	"	17 783	"	29 800	60 000	63 000
"	"	141 980	"	43 700	100 000	74 000
"	"	15 026	"	30 000	60 000	70 000
Gondola	"	6 232	S. I.	28 500	60 000	80 000
Refrigerator	"	6 003	A. R. L.	34 800	50 000	45 100
Caboose	E	98 018	I. C.	34 000		34 000

TABLE 5 TONNAGE RECORD

Test No. S-1015

Kind of Car	Loaded or Empty	Car No.	Ca Initial	Stenciled Light Weight	Capacity	Gross Weight
	L or E			pounds	pounds	pounds
Gondola	L	89 299	I. C.	32 000	80 000	82 000
‘‘	‘‘	91 712	‘‘	29 400	80 000	80 000
Box	‘‘	130 646	‘‘	42 300	80 000	92 000
Tank		500	Champ'n stock	32 100	60 000	96 000
Box	‘‘	24 678	I. C.	36 000	80 000	67 000
‘‘	‘‘	23 251	‘‘	25 200	80 000	92 300
‘‘	‘‘	140 501	‘‘	42 700	100 000	81 500
‘‘	‘‘	141 254	‘‘	43 500	100 000	96 300
Tank		185	A. P. L.			78 000
Box	‘‘	8 457	I. C.	30 100	50 000	93 100
‘‘	‘‘	26 732	‘‘	36 100	80 000	114 400
‘‘	‘‘	13 635	‘‘	28 900	60 000	84 600
‘‘	‘‘	11 069	‘‘	30 200	60 000	96 600
‘‘	‘‘	23 530	‘‘	36 100	80 000	98 000
‘‘	‘‘	12 235	‘‘	28 800	60 000	90 900
‘‘	‘‘	17 652	‘‘	28 900	60 000	83 300
‘‘	‘‘	37 500	‘‘	34 100	80 000	100 000
‘‘	‘‘	39 126	‘‘	36 700	80 000	95 500
‘‘	‘‘	17 644	‘‘	30 000	60 000	75 800
‘‘	‘‘	12 774	‘‘	30 400	60 000	81 400
‘‘	‘‘	33 666	‘‘	36 100	80 000	84 300
‘‘	‘‘	6 985	‘‘	27 700	50 000	80 600
Gondola	‘‘	86 493	‘‘	30 800	80 000	102 000
Box	‘‘	83 722	S. Pa.	33 900	80 000	123 000
‘‘	‘‘	5 000	A. R. L.	34 800	50 000	38 500
‘‘	‘‘	11 598	N. C. & St. L.	33 200	60 000	99 100
‘‘	‘‘	6 902	N. C. & St. L.	29 900	60 000	66 100
‘‘	‘‘	35 113	S. L. & S. F.	35 100	60 000	80 400
‘‘	‘‘	29 220	I. C.	38 100	60 000	53 500
Gondola	‘‘	91 289	‘‘	29 000	80 000	70 600
Flat	‘‘	8 146	I. S.	33 200	100 000	115 500
Box	‘‘	39 343	I. C.	36 600	80 000	95 000
‘‘	‘‘	141 804	‘‘	43 500	100 000	84 500
‘‘	‘‘	141 686	‘‘	43 500	100 000	103 500
‘‘	E	25 376	M.St.P.&S.SM	33 500	60 000	33 600
‘‘	L	140 755	I. C.	42 900	100 000	48 500
‘‘	‘‘	56 092	U. P.	25 800	50 000	72 800
‘‘	‘‘	15 503	I. C.	28 800	60 000	70 000
‘‘	E	13 330	C. G. W.	30 000	60 000	29 700
Flat	L	10 638	V.	24 500	60 000	33 800
‘‘	‘‘	10 521	V.	21 200	60 000	31 700
Box	‘‘	45 514	I. C.	39 100	80 000	78 600
‘‘	‘‘	142 175	‘‘	42 800	100 000	81 300
‘‘	‘‘	22 064	‘‘	37 800	80 000	76 000
‘‘	‘‘	46 450	‘‘	37 600	80 000	78 000
‘‘	‘‘	58 576	‘‘	33 800	80 000	85 000
Refrigerator	‘‘	33 476	C. & N. W.	32 200	50 000	56 000
Box	‘‘	12 530	I. C.	30 500	60 000	59 600
Tank	‘‘	990	A. P. L.			82 300
Box	‘‘	46 660	I. C.	38 000	80 000	67 400
‘‘	‘‘	49 154	‘‘	35 200	80 000	70 300
Refrigerator	‘‘	6 502	U. R. T. C.	30 800	100 000	47 700
Flat	‘‘	65 226	I. C.	23 900	60 000	71 200
Box	‘‘	140 108	‘‘	42 900	100 000	125 600
Refrigerator	‘‘	4 531	N. C. L.		50 000	41 600
Tank	‘‘	150	A. T. L.			80 100
‘‘	‘‘	153	‘‘			78 600
‘‘	‘‘	1 017	‘‘			82 000
Box	‘‘	140 161	I. C.	42 700	100 000	73 600
Tank	‘‘	904	A. T. L.			81 100
Box	E	82 244	C. & N. W.	32 600	80 000	32 800
Flat	L	1 549	C. H. & D.	21 400	50 000	26 000
‘‘	‘‘	1 799	‘‘	21 700	40 000	38 400
‘‘	‘‘	67 930	I. C.	26 800	80 000	35 700
‘‘	‘‘	878	G. & S. I.			54 700
‘‘	E	30 237	C. & H. R.	27 000	80 000	27 100
‘‘	‘‘	16 056	P. M.	22 600	60 000	22 400
Flat	‘‘	8 249	N,Y.N.H. & H.	28 900	80 000	28 800
Caboose	‘‘	98 100	I. C.			40 000

TABLE 6 Tonnage Record

Test No. S-1016

Kind of Car	Loaded or Empty	Car No.	Car Initial	Stenciled Light Weight	Capacity	Gross Weight
	L or E			pounds	pounds	pounds
Test	E	17				58 000
Gondola	"	93 191	I. C.	35 300	80 000	35 300
"	"	90 844	"	32 900	80 000	32 900
"	"	88 459	"	31 500	80 000	31 500
"	"	94 843	"	31 700	80 000	31 700
"	"	82 365	"	26 800	60 000	26 800
"	"	92 596	"	30 200	80 000	30 200
"	"	81 323	"	28 600	60 000	28 600
"	"	93 948	"	31 800	80 000	31 800
"	"	84 190	"	27 000	60 000	27 000
"	"	252	S. S. C.	25 500	50 000	25 500
"	"	616	E. F. D. & Co.	23 700	50 000	23 700
"	"	85 594	I. C.	31 400	80 000	31 400
"	"	84 200	"	27 400	60 000	27 400
"	"	95 241	"	30 100	80 000	30 100
"	"	3 252	I. S.	40 300	100 000	40 300
"	"	82 622	I. C.	27 800	60 000	27 800
"	"	106 404	"	40 300	100 000	40 300
"	"	93 494	"	29 600	60 000	29 600
"	"	86 663	"	31 100	80 000	31 100
"	"	96 262	"	31 800	80 000	31 800
"	"	95 707	"	30 800	80 000	30 800
"	"	83 544	"	28 200	60 000	28 200
"	"	93 960	"	31 300	80 000	31 300
"	"	87 697	"	33 500	80 000	33 500
"	"	96 062	"	31 400	80 000	31 400
"	"	76 634	"	25 700	50 000	25 700
"	"	91 067	"	30 200	80 000	30 200
"	"	91 424	"	30 600	80 000	30 600
"	"	89 402	"	32 000	80 000	32 000
"	"	115 127	"	42 600	100 000	42 600
"	"	106 777	"	40 300	100 000	40 300
"	"	104 930	"	40 600	100 000	40 600
"	"	95 782	"	31 500	80 000	31 500
"	"	104 131	"	40 600	100 000	40 600
"	"	92 338	"	30 600	80 000	30 600
"	"	81 653	"	26 400	60 000	26 400
"	"	96 137	"	31 000	80 000	31 000
"	"	88 950	"	31 800	80 000	31 800
"	"	115 043	"	43 200	100 000	43 200
"	"	80 128	"	28 900	60 000	28 900
"	"	94 357	"	30 900	80 000	30 900
"	"	96 123	"	31 200	80 000	31 200
"	"	91 024	"	31 000	80 000	31 000
"	"	84 272	"	27 500	60 000	27 500
"	"	85 516	"	29 400	80 000	29 400
"	"	86 283	"	31 600	80 000	31 600
"	"	87 090	"	30 900	80 000	30 900
"	"	83 604	"	27 300	60 000	27 300
"	"	80 933	"	27 500	60 000	27 500
"	"	83 243	"	28 000	60 000	28 000
"	"	85 624	"	30 800	80 000	30 800
"	"	75 812	"	26 000	50 000	26 000
"	"	85 649	"	30 700	80 000	30 700
"	"	88 925	"	31 900	80 000	31 900
"	"	93 575	"	31 100	80 000	31 100
"	"	104 318	"	40 800	100 000	40 800
"	"	86 327	"	30 400	80 000	30 400
"	"	94 273	"	30 100	80 000	30 100
"	"	80 921	"	28 200	60 000	28 200
"	"	82 167	"	26 900	60 000	26 900
"	"	101 116	"	38 500	100 000	38 500
"	"	86 515	"	30 400	80 000	30 400
"	"	88 352	"	31 200	80 000	31 200
"	"	104 944	"	40 200	100 000	40 200
"	"	105 533	"	40 500	100 000	40 500
"	"	262	S. S. C.	30 600	80 000	30 600
"	"	89 849	I. C.	32 000	80 000	32 000
"	"	95 296	"	30 000	80 000	30 000
"	"	93 197	"	31 400	80 000	31 400
"	"	106 428	"	40 300	100 000	40 300
Caboose	"	98 172	"	40 000		40 000

TABLE 7 Tonnage Record

Test No. S-1017

Kind of Car	Loaded or Empty	Car No.	Car Initial	Stenciled Light Weight	Capacity	Gross Weight
	L or E			pounds	pounds	pounds
Box	L	32 302	I. C.	32 500	60 000	96 500
Gondola	"	3 363	I. S.	40 300	100 000	140 800
Box	"	9 009	I. C.	27 700	50 000	74 000
"	"	48 654	"	38 500	80 000	96 100
"	"	12 968	"	29 200	60 000	65 100
"	"	150 867	"	30 000	40 000	73 700
"	"	17 772	"	29 400	60 000	90 800
"	"	10 673	"	31 700	60 000	96 800
"	"	130 783	"	42 300	80 000	130 600
"	"	150 961	"	30 500	40 000	75 900
"	"	11 350	"	29 700	60 000	69 300
Refrigerator	"	6 638	U. R. T.	34 800	40 000	52 000
Box	"	141 330	I. C.	43 700	100 000	76 000
"	"	141 589	"	43 600	100 000	114 000
"	"	24 682	"	35 800	80 000	80 000
"	"	22 896	"	37 000	80 000	86 000
"	"	24 158	"	35 500	80 000	72 000
"	"	22 041	"	37 800	80 000	86 000
"	E	107 946	C. & N. W.	36 600	80 000	37 000
"	L	47 421	I. C.	41 500	80 000	116 000
"	"	10 485	"	29 400	60 000	92 800
"	"	130 247	"	42 400	80 000	132 000
"	"	22 942	"	36 800	80 000	123 800
"	"	22 968	"	36 600	80 000	115 700
"	"	141 969	"	43 500	100 000	119 500
"	"	32 317	"	31 100	60 000	98 400
"	"	22 318	"	38 200	80 000	56 700
"	"	11 165	"	30 300	60 000	71 800
"	"	8 390	"	31 200	60 000	77 500
"	"	142 726	"	42 800	100 000	62 000
"	"	7 698	L. & N.	28 400	60 000	60 000
"	"	1 807	"	34 200	65 000	98 000
Refrigerator	E	4 056	M. R. T.	40 400	60 000	40 000
Box	"	53 873	C. R. I. & P.	32 400	60 000	32 000
"	"	56 432	C. M. & St. P.	29 900	60 000	29 000
"	L	35 199	I. C.	36 800	80 000	105 200
"	E	10 428	W. C.	29 400	60 000	29 700
"	"	2 786	A. & W. P.	35 000	65 000	33 200
Refrigerator	"	397	W. R. T.	34 700	40 000	35 000
Gondola	"	1 025	C. & I. W.	32 200	100 000	32 000
Box	L	49 236	I. C.	34 800	80 000	103 000
"	"	14 943	"	30 800	60 000	84 600
"	"	17 142	"	30 500	60 000	84 000
"	"	22 404	"	27 900	80 000	109 000
"	"	150 265	"	29 300	40 000	65 000
"	"	5 298	Ga.	31 800	60 000	73 100
"	"	14 010	I. C.	32 200	60 000	68 900
"	"	36 980	"	31 300	80 000	81 000
"	"	48 699	"	39 300	80 000	59 300
"	"	48 721	"	39 200	80 000	77 500
"	"	21 715	"	36 200	80 000	81 500
"	"	1 292	I. L. & M.	29 200	60 000	113 000
"	"	142 255	I. C.	42 900	100 000	97 500
"	"	45 525	"	39 300	80 000	75 700
Refrigerator	E	9 056	C. R. D.	34 600		34 600
Box	L	48 739	I. C.	39 100	80 000	74 100
"	"	45 762	"	40 300	80 000	78 700
"	E	36 636	"	34 100	80 000	35 300
"	L	22 995	"	35 100	80 000	94 300
Gondola	"	106 302	"	40 300	100 000	90 500
Box	E	72 344	C. M. & St. P.	30 400	60 000	29 000
"	L	19 840	I. C.	29 300	60 000	64 300
"	"	17 625	"	29 300	60 000	58 000
"	E	64 599	N. & W.	39 500	80 000	38 800
"	L	45 386	I. C.	38 700	80 000	79 800
Caboose	E	98 023	"			40 000

TABLE 8 TONNAGE RECORD

Test No. S-1018

Kind of Car	Loaded or Empty	Car No.	Car Initial	Stenciled Light Weight	Capacity	Gross Weight
	L or E			pounds	pounds	pounds
Test	E	17				58 000
Box	L	28 594	A. T. & S. F.	36 700	70 000	113 600
‘‘	‘‘	73 246	C. & N. W.	29 800	80 000	92 600
‘‘	E	49 016	I. C.	39 300	60 000	44 200
‘‘	L	16 179	‘‘	29 700	80 000	38 400
Gondola	‘‘	104 113	‘‘	40 800	100 000	131 400
Box	E	46 485	‘‘	37 800	80 000	43 400
‘‘	L	24 331	S. A. L.	28 900	60 000	39 200
‘‘	E	5 372	L. R. & M.	34 600	60 000	34 400
‘‘	‘‘	251	O. G. & N. E.	38 700	80 000	38 800
‘‘	‘‘	19 944	South	31 900	60 000	33 600
Gondola	‘‘	180 614	‘‘	40 100	100 000	37 200
Box	‘‘	56 649	L. & N.	41 100	50 000	42 800
‘‘	L	45 413	Big 4.	38 100	80 000	82 200
‘‘	‘‘	49 161	T. C.	35 800	80 000	59 400
‘‘	E	68 250	C. & N. W.	30 000	60 000	39 200
‘‘	L	39 546	‘‘	33 500	60 000	51 000
Locomotive		423	I. C.			145 200
Flat	L	66 644	‘‘	29 000	80 000	65 800
Tank	‘‘	6 059	S. I.		8 000 Gal.	35 200
‘‘	E	6 052	‘‘		8 000 Gal.	41 600
‘‘	‘‘	6 239	‘‘		8 000 Gal.	39 000
‘‘	‘‘	6 233	‘‘		8 000 Gal.	39 400
‘‘	‘‘	6 054	‘‘		8 000 Gal.	38 400
‘‘	‘‘	6 190	‘‘		8 000 Gal.	39 800
‘‘	‘‘	600	I. T. Co.	30 000	80 000	39 200
Box	‘‘	130 857	I. C.	41 000	80 000	80 800
Tank	L	680	S. C. O. Co.	48 100	12 500 Gal.	49 200
Gondola	‘‘	3 175	I. S.	40 400	100 000	148 000
‘‘	E	273	S. C. Co.	30 700	80 000	35 800
Locomotive		732	I. C.			223 600
Box	E	30 105	M. L. & T.	33 100	80 000	33 400
‘‘	‘‘	11 571	A. G. S.	34 700	60 000	34 400
‘‘	‘‘	2 004	D. & W.	36 900	60 000	36 200
‘‘	‘‘	14 533	L. & N.	33 300	65 000	34 600
‘‘	L	558 937	Penn.	45 400	100 000	71 400
‘‘	‘‘	84 494	P. R. R.	30 800	60 000	55 600
‘‘	E	9 230	N. C. & St. L.	33 300	60 000	34 000
‘‘	L	9 264	‘‘	30 200	60 000	34 600
‘‘	E	6 316	‘‘	29 100	60 000	29 800
‘‘	‘‘	135 068	South	33 500	60 000	33 500
‘‘	‘‘	13 161	‘‘	33 800	60 000	33 800
‘‘	‘‘	13 761	St. L. & S. F.	34 000	60 000	34 000
‘‘	‘‘	32 482	South	35 600	60 000	34 000
Flat	‘‘	1 276	G. S. I.	28 600	80 000	27 000
‘‘	‘‘	803	M. C.	28 500	80 000	28 500
‘‘	‘‘	621	‘‘	28 500	80 000	28 500
‘‘	‘‘	413	G. S. F.	27 200	60 000	27 800
‘‘	‘‘	553	‘‘	27 200	60 000	27 600
‘‘	‘‘	799	‘‘	27 500	80 000	27 500
Caboose	‘‘		I. C.			40 000

TABLE 9 TONNAGE RECORD

Test No. S-1019

Box	E	46 712	I. C.	38 100	80 000	38 100
‘‘	‘‘	38 898	‘‘	36 700	80 000	38 600
‘‘	‘‘	14 965	‘‘	30 100	60 000	30 400
‘‘	‘‘	35 160	‘‘	36 900	80 000	36 900
Flat	L	500	A. T. L. Co,	41 720	60 000	103 000
Box	‘‘	25 173	I. C.	37 100	80 000	70 000
‘‘	‘‘	19 287	S. A. L.	33 300	80 000	62 000
‘‘	‘‘	11 539	N. C. & St. L	33 800	60 000	4 300
‘‘	‘‘	997	P. M	34 400	50 000	50 100
‘‘	‘‘	1 853	D & M.	33 100	60 000	71 100
‘‘	‘‘	3 768	N. C. & St. L	37 100	60 000	62 600
‘‘	‘‘	57 378	C. M. & St. P	29 900	80 000	70 000
‘‘	‘‘	33 580	I. C.	36 000	80 000	74 000
‘‘	E	55 968	L. & N.	41 400	55 000	42 000
‘‘	‘‘	46 836	I. C.	38 100	80 000	36 500
‘‘	L	16 200	‘‘	30 000	50 000	30 000

TABLE 9 Tonnage Record—(*Continued*)

Kind of Car	Loaded or Empty	Car No.	Car Intitial	Stenciled Light Weight	Capacity	Gross Weight
	L or E			pounds	pounds	pounds
Box	E	12 296	I. C.	29 400	60 000	29 000
"	"	12 302	"	29 700	60 000	30 000
"	"	37 189	"	34 500	80 000	35 000
"	"	24 525	"	36 400	80 000	36 400
"	"	37 157	"	33 600	80 000	34 500
Gondola	"	88 956	"	31 900	80 000	32 000
"	"	90 907	"	30 900	80 000	32 000
"	"	81 808	"	28 800	60 000	28 000
"	"	96 187	"	30 500	80 000	32 100
"	"	87 235	"	31 400	80 000	31 400
"	"	86 649	"	30 900	80 000	30 800
Box	"	30 249	T. R. E.	38 700	50 000	38 700
Refrigerator	"	19 529	C. F. X.	34 400	50 000	37 200
Tank	L	6 278	C. T. L.	47 000		95 200
Box	"	45 246	I. C.	37 400	80 000	37 200
"	"	142 342	"	42 700	100 000	42 700
"	E	141 780	"	43 600	100 000	43 100
"	L	7 613	"	27 100	50 000	27 100
Gondola	E	105 880	"	40 399	100 000	40 400
"	"	86 524	"	31 200	80 000	31 400
"	"	104 438	"	40 700	100 000	40 800
"	"	106 223	"	40 400	100 000	41 000
"	"	94 144	"	31 000	80 000	32 000
"	"	93 670	"	30 000	80 000	30 400
"	"	5 470	"	23 200	50 000	23 100
"	"	94 433	"	30 900	80 000	30 600
"	"	87 576	"	31 500	80 000	32 100
"	"	81 635	"	27 700	60 000	26 900
"	"	87 931	"	31 900	80 000	31 800
"	"	86 493	"	30 800	80 000	31 100
"	"	89 415	"	31 700	80 000	32 100
"	"	90 560	"	32 200	80 000	32 300
"	"	83 302	"	28 400	60 000	28 400
"	"	83 372	"	28 600	60 000	28 600
"	"	92 680	"	30 900	80 000	30 900
"	"	95 924	"	31 700	80 000	32 100
"	"	89 504	"	32 000	80 000	32 400
"	"	91 813	"	29 600	80 000	30 000
"	"	86 821	"	32 200	80 000	32 300
"	"	81 851	"	28 700	60 000	28 900
"	"	90 634	"	32 300	80 000	32 500
"	"	82 958	"	28 400	60 000	28 400
"	"	91 289	"	29 000	80 000	30 100
"	"	89 443	"	31 800	80 000	32 100
"	"	95 945	"	31 800	80 000	32 000
"	"	94 941	"	31 000	80 000	30 900
"	"	85 915	"	31 600	80 000	31 900
"	"	87 758	"	31 000	80 000	31 800
"	"	91 822	"	30 400	80 000	30 600
"	"	91 482	"	30 300	80 000	30 400
"	"	96 285	"	32 000	80 000	32 000
"	"	83 017	"	27 300	60 000	28 100
"	"	101 052	"	38 500	100 000	39 500
Box	"	82 279	"	28 100	60 000	28 200
"	"	31 042	I. S.	36 300	60 000	36 500
"	"	22 320	I. C.	31 000	60 000	31 500
Gondola	"	6 391	"	24 200	60 000	24 200
"	"	94 066	"	30 500	80 000	31 100
"	"	90 487	"	31 600	80 000	31 900
"	"	86 903	"	31 000	80 000	31 000
"	"	93 952	"	31 400	80 000	31 700
"	"	91 861	"	33 700	80 000	33 100
"	"	86 214	"	30 700	80 000	31 100
"	"	88 076	"	31 700	80 000	31 400
"	"	90 050	"	31 000	80 000	31 000
"	"	85 151	"	31 300	80 000	31 200
"	"	83 526	"	27 300	60 000	27 900
Flat	"	790	"	27 100	80 000	27 000
"	"	1 202	M. C.	28 100	80 000	28 100
"	"	590	C. S. I	27 400	80 000	27 400
"	"	272	C. S. I	24 400	60 000	29 400
"	"	825	M. C.	28 500	80 000	28 400
Caboose	"	98 600	I. C.			40 000

TABLE 10 Tonnage Record

Test No. S-1021

K Car	Loaded or Empty	Car No.	Car Initial	Stenciled Light Weight	Capacity	Gross Weight
	L or E			pounds	pounds	pounds
Test	E	17				58 000
Gondola	L	97 430	I. C.	31 400	100 000	104 600
"	"	95 341	"	30 100	80 000	105 000
"	"	88 198	"	33 000	80 000	98 000
"	"	105 823	"	40 400	100 000	152 000
"	"	90 733	"	31 400	80 000	107 000
"	"	87 110	"	32 000	80 000	108 300
"	"	88 418	"	32 000	80 000	105 600
"	"	84 458	"	30 800	60 000	87 000
"	"	88 321	"	32 600	80 000	109 000
"	"	81 982	"	29 400	60 000	88 000
"	"	91 087	"	30 700	80 000	110 700
"	"	92 434	"	31 400	80 000	106 900
"	"	110 325	"	41 600	100 000	135 800
"	"	3 380	I. S.	40 400	100 000	144 000
"	"	83 881	I. C.	28 900	60 000	87 700
"	"	84 313	"	27 300	60 000	86 000
"	"	92 813	"	30 700	80 000	110 000
"	"	100 242	"	33 100	90 000	124 400
Box	"	47 936	"	39 000	80 000	104 000
"	"	17 469	"	29 000	60 000	70 600
Tank	E	6 355	C. T. L.			38 300
"	"	6 315	"			37 800
Box	L	22 469	I. C.	38 600	80 000	81 700
"	"	9 858	N. C. & St. L.	33 900	60 000	66 200
Gondola	"	104 238	I. C.	40 500	100 000	148 500
"	"	89 092	"	32 500	80 000	115 500
"	"	101 130	"	36 700	100 000	134 700
"	"	82 069	"	29 000	60 000	88 000
"	"	81 382	"	26 900	60 000	83 000
Box	"	130 860	"	42 300	80 000	96 000
"	"	82 292	S. P.	34 200	80 000	75 000
"	"	56 120	C. & N. W.	31 500	50 000	58 000
"	"	12 655	I. C.	29 000	60 000	58 000
Flat	"	66 686	"	28 000	80 000	105 000
"	"	131 191	"	39 500	80 000	95 000
Refrigerator	E	9 547	A. R. L.	38 700	50 000	40 000
Box	L	7 304	H. & T. C.	30 400	60 000	69 000
"	"	130 987	I. C.	42 300	80 000	78 000
Gondola	"	86 023	"	31 200	80 000	118 000
Refrigerator	E	2 130	C. R. D.			41 000
Box	"	74 674	C. & N. W.	34 000	80 000	34 000
Gondola	L	104 603	I. C.	40 500	100 000	149 000
"	"	104 872	"	40 000	100 000	146 000
"	"	105 603	"	40 200	100 000	143 800
Refrigerator	E	6 417	A. R. L.	31 300	50 000	35 800
"	"	50 564	I. C.	35 600	50 000	36 000
Flat	L	807	G. & S. I.	26 400	80 000	61 800
Box	"	39 641	I. C.	36 300	80 000	47 900
Refrigerator	E	3 031	P. B. C.	30 700	40 000	33 700
Box	L	11 344	H. & R.	42 000	100 000	111 200
Gondola	"	87 136	I. C.	31 700	80 000	112 400
"	"	83 896	"	26 600	60 000	86 000
"	"	90 589	"	33 300	80 000	112 000
"	"	87 685	"	31 800	80 000	109 400
"	"	93 498	"	31 000	80 000	107 800
"	"	95 054	"	30 200	80 000	108 000
"	"	100 041	"	34 400	90 000	123 000
"	"	97 555	"	31 800	80 000	99 000
"	"	220	S. L. B. & S.	28 000	60 000	89 000
"	"	95 342	I. C.	29 000	80 000	105 000
"	"	97 459	"	31 400	100 000	103 000
Caboose	E		"			34 000

TABLE 11 Tonnage Record

Test No. S-1023

Kind of Car	Loaded or Empty	Car No.	Car Initial	Stenciled Light Weight	Capacity	Gross Weight
	L or E			pounds	pounds	pounds
Test	E	17				58 000
Box	L	141 953	I. C.	43 500	100 000	76 000
Gondola	"	104 462	"	40 700	100 000	110 000
"	"	95 110	"	30 000	80 000	83 000
"	"	110 088	"	41 000	100 000	100 000
"	"	95 949	"	30 900	80 000	79 000
Tank	"	59	R. O. R. Co.		80 000	58 000
Box	"	80 880	P. R. R.	33 500	80 000	74 000
"	"	10 951	N. C. & St. L.	32 700	60 000	88 000
"	E	133 684	Southern	33 200	60 000	33 000
Gondola	L	85 410	I. C.	33 300	80 000	93 000
"	"	80 355	"	27 100	60 000	80 000
"	"	90 035	"	29 500	80 000	112 000
Box	"	11 893	L. & N.	30 400	60 000	75 000
Gondola	"	85 248	I. C.	31 000	80 000	112 000
"	"	89 009	"	32 200	80 000	106 000
"	"	94 119	"	31 100	80 000	113 000
"	"	81 946	"	28 400	60 000	96 000
"	"	84 309	"	27 500	60 000	92 000
"	"	88 551	"	32 400	80 000	103 000
"	"	87 027	"	31 700	80 000	95 000
"	"	87 989	"	32 100	80 000	110 000
"	"	90 347	"	33 000	80 000	111 000
"	"	80 226	"	24 700	60 000	80 000
"	"	84 268	"	29 500	60 000	78 000
"	"	100 190	"	34 400	90 000	124 000
"	"	110 196	"	40 800	100 000	133 000
"	"	106 943	"	40 300	100 000	143 000
"	"	80 936	"	27 900	60 000	87 000
"	"	90 907	"	30 900	80 000	108 000
"	"	82 970	"	26 900	60 000	88 000
"	"	104 451	"	40 700	100 000	133 800
"	"	84 142	"	28 200	60 000	89 000
"	"	89 380	"	31 800	80 000	108 000
Box	"	39 074	"	38 300	80 000	94 000
"	"	141 730	"	43 700	100 000	105 000
Refrigerator	E	6 492	N.C. L. C.		60 000	43 000
Box	L	10 049	I. C.	30 800	60 000	36 000
Refrigerator	E	301	U. R. T. Co.	41 100	50 000	39 000
Box	"	155	S. H. C. Co.	40 800	60 000	40 000
"	"	2 056	G. B. & W.	31 400	60 000	31 000
"	"	108 260	Erie	40 100	80 000	38 900
"	L	7 220	I. C.	25 500	50 000	77 800
"	E	28 475	"	36 500	60 000	52 800
Tank	L	708	D. R. & U.			76 000
Box	E	48 782	I. C	39 100	80 000	55 000
Gondola	"	50 861	Erie	40 900	100 000	41 000
"	"	16 977	"	42 800	100 000	42 800
Box	L	141 005	I. C.	43 600	100 000	80 000
Gondola	"	57 131	B. & O.	28 200	60 000	67 000
Box	E	83 308	C. & N. W.	32 600	80 000	32 000
"	"	56 189	U. P.	28 000	50 000	28 000
"	"	78 219	C. & N. W.	34 450	80 000	34 000
"	"	48 596	"	28 300	40 000	28 400
"	"	86	S. H. C. Co.	40 800	60 000	39 000
"	L	13 803	I. C.	29 100	60 000	71 000
"	"	14 437	"	29 500	60 000	65 000
Caboose	E	98 026	"			40 000

TABLE 12 TONNAGE RECORD

Test No. S-1027

Kind of Car	Loaded or Empty	Car No.	Car Initial	Stenciled Light Weight	Capacity	Gross Weight
	L or E			pounds	pounds	pounds
Test	E	17				58 000
Gondola	L	104 866	I. C.	40 300	100 000	146 700
"	"	104 482	"	36 000	100 000	148 100
"	"	106 662	"	40 200	100 000	146 000
Box	"	15 035	"	29 200	60 000	52 000
"	"	17 391	"	30 000	60 000	59 800
Gondola	"	3 008	I. S.	40 200	100 000	135 400
"	"	609	C. C. & Co.	31 700	80 000	105 900
"	"	622	C. C. & Co.	31 700	80 000	106 500
"	"	92 361	I. C.	33 000	80 000	109 800
"	"	104 423	"	40 900	100 000	139 300
"	"	3 054	I. S.	40 100	100 000	142 400
"	"	105 824	I. C.	40 300	100 000	122 000
"	"	80 466	"	26 700	60 000	84 000
"	"	92 965	"	30 800	80 000	98 000
"	"	94 160	"	31 400	80 000	100 200
"	"	85 775	"	31 200	80 000	100 300
"	"	88 635	"	31 400	80 000	104 400
"	"	83 229	"	27 200	60 000	81 000
"	"	81 193	"	27 300	60 000	83 600
"	"	80 822	"	27 500	60 000	81 900
"	"	104 540	"	40 500	100 000	142 000
"	"	94 317	"	30 800	80 000	108 500
"	"	91 922	"	30 400	80 000	101 800
"	"	91 551	"	28 800	80 000	105 800
"	"	88 090	"	31 500	80 000	101 100
"	"	93 860	"	30 300	80 000	107 100
"	"	80 089	"	28 900	60 000	80 800
"	"	75 482	"	23 000	50 000	65 900
"	"	86 315	"	31 000	80 000	103 200
"	"	629	C. C. & Co.	31 700	80 000	106 500
"	"	76 275	I. C.	24 800	50 000	78 300
"	"	16 225	W. M.	39 100	80 000	117 300
"	"	87 491	I. C.	32 000	80 000	101 800
"	"	93 520	"	29 800	80 000	104 700
Box	"	10 931	T. & N. O.	30 700	60 000	64 100
"	"	21 957	I. C.	38 200	80 000	104 500
Gondola	"	85 133	"	31 500	80 000	62 700
Box	"	33 362	C. & N.	32 400	50 000	38 000
Gondola	"	88 516	I. C.	31 800	80 000	918 000
Box	"	1 614	C. & O.	37 700	80 000	90 100
"	"	7 542	I. C.	28 200	50 000	75 000
"	"	17 356	"	30 100	60 000	73 000
Flat	"	69 086	"	33 100	100 000	75 000
"	E	67 114	"	25 600	80 000	27 600
Caboose	"		"			38 000

TABLE 13 TONNAGE RECORD

Test No. S-1030A

Kind of Car	Loaded or Empty	Car No.	Car Initial	Stenciled Light Weight	Capacity	Gross Weight
	L or E			pounds	pounds	pounds
Test	E	17				58 000
Gondola	L	110 699	I. C.	41 100	100 000	130 900
"	"	111 182	"	40 700	100 000	129 400
"	"	87 386	"	30 700	80 000	109 300
"	"	3 264	I. S.	40 400	100 000	142 300
"	"	101 209	I. C.	38 100	100 000	145 000
"	"	106 217	"	40 400	100 000	144 500
"	"	25 601	"	31 300	80 000	105 800
"	"	101 160	"	40 200	100 000	145 000
"	"	105 667	"	40 300	100 000	142 600
"	"	101 052	"	38 500	100 000	143 600
"	"	96 213	"	31 900	80 000	106 200
"	"	106 868	"	40 200	100 000	145 200
"	"	81 275	"	29 700	60 000	88 400
"	"	82 959	"	27 900	60 000	87 600
"	"	89 028	"	33 600	80 000	109 600
"	"	81 296	"	28 800	60 000	86 600
"	"	111 248	"	40 800	100 000	133 000
"	"	3 375	I. S.	40 500	100 000	147 000
"	"	104 037	I. C.	40 900	100 000	147 000
"	"	86 480	"	32 000	80 000	119 000
"	"	104 366	"	40 400	100 000	154 800
"	"	92 183	"	31 000	80 000	116 900
"	"	94 862	"	32 600	80 000	117 400
"	"	94 539	"	32 100	80 000	119 200
"	"	104 877	"	40 300	100 000	154 000
"	"	93 341	"	30 700	80 000	118 600
"	"	86 032	"	29 800	80 000	111 500
"	"	89 078	"	31 900	80 000	113 400
"	"	88 556	"	32 200	80 000	110 500
"	"	96 794	"	32 000	100 000	113 000
"	"	88 577	"	32 400	80 000	111 200
"	"	100 243	"	32 800	90 000	125 500
Caboose	E	98 016	"			40 000

TABLE 14 Tonnage Record Test No. S-1030B

Kind of Car	Loaded or Empty	Car No.	Car Initial	Stenciled Light Weight	Capacity	Gross Weight
	L or E			pounds	pounds	pounds
Test	E	17				58 000
Gondola	L	110 699	I. C.	41 100	100 000	130 900
"	"	111 182	"	40 700	100 000	129 400
"	"	87 386	"	30 700	80 000	109 300
"	"	3 264	I. S.	40 400	100 000	142 300
"	"	101 209	I. C.	38 100	100 000	145 000
"	"	106 217	"	40 400	100 000	144 500
"	"	25 601	"	31 300	80 000	105 800
"	"	101 160	"	40 200	100 000	145 000
"	"	105 667	"	40 300	100 000	142 600
"	"	101 052	"	38 500	100 000	143 600
"	"	96 213	"	31 900	80 000	106 200
"	"	106 868	"	40 200	100 000	145 200
"	"	81 275	"	29 700	60 000	88 400
"	"	82 959	"	27 900	60 000	87 600
"	"	89 028	"	33 600	80 000	109 600
"	"	81 296	"	28 800	60 000	86 600
"	"	111 248	"	40 800	100 000	133 000
"	"	3 375	I S.	40 500	100 000	147 000
"	"	104 037	I. C.	40 900	100 000	147 000
"	"	86 480	"	32 000	80 000	119 000
"	"	104 366	"	40 400	100 000	154 800
"	"	92 183	"	31 000	80 000	116 900
"	"	94 862	"	32 600	80 000	117 400
"	"	94 539	"	32 100	80 000	119 200
"	"	104 877	"	40 300	100 000	154 000
"	"	93 341	"	30 700	80 000	118 600
"	"	86 032	"	29 800	80 000	111 500
"	"	89 078	"	31 900	80 000	113 400
"	"	88 556	"	32 200	80 000	110 500
"	"	96 794	"	32 000	100 000	113 000
"	"	88 577	"	32 400	80 000	111 200
"	"	100 243	"	32 800	90 000	125 500
Box	"	91 482	L. & N.	35 300	65 000	106 100
Gondola	"	66 107	"	37 200	80 000	102 920
Box	E	95 645	M. C.	39 800	60 000	40 000
"	L	13 470	S.	32 600	60 000	50 000
"	"	142 610	I. C.	42 900	100 000	151 900
"	"	14 474	C. N. O. & T. P.	34 800	60 000	71 700
"	"	11 845	L. & N.	30 400	60 000	88 600
Caboose	E	98 016	I. C.			40 000

TABLE 15 Tonnage Record Test No. S-1031

Box	E	34 853	I. C.	37 300	80 000	37 300
"	"	37 120	"	34 300	80 000	34 300
"	"	33 101	"	37 800	80 000	37 900
"	"	11 771	"	29 500	60 000	29 500
"	"	24 366	"	36 500	80 000	36 500
"	"	45 812	"	39 000	80 000	39 000
"	"	35 859	"	36 300	80 000	36 300
"	"	49 227	"	35 600	80 000	35 700
"	"	37 430	"	35 000	80 000	35 100
"	"	48 723	"	39 100	80 000	39 200
"	"	15 256	"	29 500	60 000	29 500
"	"	18 369	"	28 900	60 000	28 800
"	"	46 321	"	37 100	80 000	37 100
"	"	26 699	"	36 300	80 000	36 200
"	"	38 079	"	33 700	80 000	33 700
"	"	49 040	"	38 000	80 000	38 100
"	"	25 514	"	35 500	80 000	35 500
"	"	34 974	"	36 500	80 000	36 600
"	"	24 617	"	35 800	80 000	35 600
"	"	47 800	"	37 700	80 000	37 700
"	"	141 461	"	43 600	100 000	43 600
"	"	140 995	"	42 800	100 000	42 800
"	"	49 435	"	33 800	80 000	33 800
"	"	36 259	"	36 400	80 000	36 400
"	"	16 183	"	30 000	60 000	30 000
"	L	49 414	"	35 300	80 000	59 050
"	"	22 932	"	37 400	80 000	72 900
"	"	19 896	"	29 100	60 000	73 800

TABLE 15—(*Continued*)

Kind of Car	Loaded or Empty	Car No.	Car Initial	Stenciled Light Weight	Capacity	Gross Weight
	L or E			pounds	pounds	pounds
"	"	20 289	"	28 600	60 000	74 300
"	"	15 490	"	29 900	60 000	73 500
"	"	49 183	"	35 500	80 000	74 100
"	E	6 909	L. & N.	30 900	60 000	30 700
Gondola	"	18 273	S.	40 100	100 000	40 300
Box	"	19 508	St. L. & S. W.	32 000	60 000	32 100
Flat	"	66 887	I. C.	27 600	80 000	27 300
Caboose	"	98 119	"			40 000

TABLE 16 TONNAGE RECORD Test No. S-1033

Test	E	17				58 000
Gondola	L	49 085	N, & W.	37 900	80 000	124 000
"	"	731	C. C. & Co.	31 700	80 000	110 000
"	"	708	"	31 600	80 000	104 600
"	"	619	"	31 700	80 000	104 000
"	"	742	"	31 700	80 000	108 300
"	"	748	"	31 700	80 000	104 300
"	"	104 775	I. C,	40 300	100 000	132 400
"	"	104 149	"	40 700	100 000	133 100
"	"	83 232	"	28 300	60 000	88 900
"	"	12 076	D	33 500	80 000	97 100
"	"	89 448	I. C.	31 800	80 000	109 000
"	"	89 505	"	32 500	80 000	106 400
"	"	47 043	N. & W.	32 000	85 000	99 000
"	"	79 189	I. C.	24 500	50 000	72 700
"	"	666	L . . A. & W.	40 600	60 000	92 800
"	"	115 003	I. C.	43 000	100 000	122 300
"	"	85 906	"	34 600	80 000	113 000
"	"	83 928	"	26 500	60 000	77 000
"	"	106 446	"	39 600	100 000	133 100
"	"	104 846	"	40 200	100 000	142 000
"	"	86 763	"	32 100	80 000	104 000
"	"	97 319	"	32 900	100 000	98 000
"	"	97 061	"	31 900	100 000	101 000
"	"	81 968	"	26 400	60 000	88 100
"	"	707	C. C. Co,	31 700	80 000	107 000
"	"	94 140	I. C.	31 600	80 000	98 000
"	"	88 213	"	31 900	80 000	105 000
"	"	86 642	"	31 300	80 000	106 000
"	"	111 336	"	40 100	100 000	126 000
"	"	80 952	"	26 000	60 000	84 000
"	"	79 077	"	34 900	50 000	82 000
"	"	14 722	M. & O.	33 900	80 000	95 100
"	"	106 167	I. C.	40 300	100 000	136 000
"	"	90 535	"	32 700	80 000	102 000
"	"	93 442	"	29 500	80 000	104 600
"	"	16 738	Erie	42 800	100 000	102 800
"	"	85 379	I. C.	31 200	80 000	110 900
"	"	87 672	"	31 300	80 000	104 000
"	"	30 456	C. & B.	39 100	100 000	128 000
"	"	80 855	I. C.	28 300	60 000	86 100
"	"	85 959	"	31 000	80 000	103 100
"	"	644	C. C. Co.	31 700	80 000	106 100
Caboose	E	19 510	I. C.			40 000

TABLE 17 Tonnage Record Test No. S-1034

Kind of Car	Loaded or Empty	Car No.	Car Initial	Stenciled Light Weight	Capacity	Gross Weight
	L or E			pounds	pounds	pounds
Gondola	E	80 223	I. C.	26 900	60 000	25 200
"	"	89 617	"	32 200	80 000	32 400
"	"	110 863	"	41 000	100 000	41 200
"	"	34 775	N. Y. C.	41 600	100 000	41 700
"	"	86 158	I. C.	31 300	80 000	31 100
"	"	80 338	"	24 500	60 000	23 900
"	"	87 806	"	31 500	80 000	31 500
"	"	96 249	"	30 900	80 000	30 500
"	"	9 038	T, & O. C.	26 700	60 000	24 500
"	"	79 089	I. C.	23 200	50 000	23 300
"	"	93 123	"	31 100	80 000	31 800
"	"	82 546	"	27 900	60 000	27 500
"	"	104 295	"	40 500	100 000	40 400
"	"	89 543	"	30 900	80 000	31 300
"	"	110 722	"	41 500	100 000	41 700
"	"	92 260	"	31 100	80 000	30 500
"	"	84 227	"	28 400	60 000	27 200
"	"	81 254	"	27 400	60 000	26 700
"	"	85 110	"	31 400	80 000	30 400
"	"	105 192	"	40 300	100 000	40 200
"	"	15 248	Van. Line	40 700	100 000	40 600
"	"	92 465	I. C.	31 200	80 000	30 200
"	"	90 716	"	31 400	80 000	30 700
"	"	800 312	Penn.	38 400	100 000	38 300
"	"	3 190	I. S.	40 600	100 000	40 400
"	"	47 608	N. & W.	32 600	85 000	34 000
"	"	93 502	I. C.	30 100	80 000	30 400
"	"	105 620	"	40 300	100 000	40 100
"	"	85 250	"	30 400	80 000	30 900
"	"	90 396	"	31 000	80 000	30 900
"	"	3 183	I. S.	40 400	100 000	40 600
"	"	96 492	I. C.	31 000	80 000	30 300
"	"	104 730	"	40 400	100 000	40 500
"	"	104 667	"	40 700	100 000	40 600
"	"	94 692	"	32 000	80 000	32 100
"	"	82 744	"	27 900	60 000	28 600
"	"	282 388	Penn.	45 000	100 000	40 400
"	"	94 128	I. C.	30 300	80 000	30 100
"	"	94 783	"	31 200	80 000	30 900
"	"	104 702	"	40 600	100 000	40 500
"	"	96 797	"	31 400	100 000	33 200
"	"	96 917	"	30 200	80 000	30 200
"	"	106 219	"	40 300	100 000	40 200
"	"	28 743	C. & O.	39 900	100 000	38 700
"	"	83 171	I. C.	28 400	60 000	27 200
"	"	96 089	"	31 000	80 000	31 000
"	"	49 415	N. & W.	38 200	100 000	37 100
"	"	93 048	I. C.	31 600	80 000	31 000
"	"	13 930	C. & O.	25 000	60 000	25 300
"	"	13 648	N. & W.	34 100	80 000	34 000
"	"	29 059	C. & O.	41 400	100 000	41 000
"	"	14 840	"	30 900	80 000	30 300
"	"	76 008	I. C.	24 300	50 000	23 000
"	"	86 763	"	32 100	80 000	30 700
"	"	83 969	"	26 200	60 000	27 200
"	"	88 028	"	30 400	80 000	31 400
"	"	89 502	"	31 800	80 000	31 500
"	"	806 908	"	40 200	100 000	40 100
"	"	68 698	L. & N.	35 400	80 000	35 500
"	"	81 422	I. C.	26 800	60 000	27 000
"	"	106 388	"	40 800	100 000	40 800
"	"	11 625	C. & E. I.	32 400	80 000	31 000
"	"	75 084	"	38 400	100 000	38 900
"	"	3 393	I. S.	40 100	100 000	40 000
"	"	105 811	I. C.	40 400	100 000	40 800
"	"	91 161	"	30 000	80 000	29 600
"	"	27 237	Big Four	22 500	50 000	24 600
"	"	33 336	L. & N.	28 400	66 000	28 500
"	"	91 941	I. C.	33 000	80 000	31 300
"	"	106 191	"	40 000	100 000	40 200
"	"	78 930	"	25 200	50 000	23 500
"	"	85 198	"	31 300	80 000	30 500
"	"	91 102	"	31 300	80 000	29 700
"	"	32 243	L. & N.	30 400	66 000	30 200
"	"	44 069	N. & W.	38 100	100 000	38 000
Caboose	"	98 465	I. C.			40 000

TABLE 18 Tonnage Record

Test No. S-1036

Kind of Car	Loaded or Empty	Car No.	Car Initial	Stenciled Light Weight	Capacity	Gross Weight
	L. or E.			pounds	pounds	pounds
Test	E	17				58 000
Flat	L	65 913	I. C.	27 900	80 000	79 600
Gondola	"	81 595	"	27 500	60 000	90 000
"	"	97 929	"	31 100	80 000	98 000
"	"	95 885	"	31 000	80 000	106 000
"	"	87 632	"	31 700	80 000	108 400
"	"	96 914	"	31 900	100 000	105 000
"	"	76 735	"	25 200	50 000	78 000
"	"	84 272	"	37 500	60 000	76 000
"	"	91 429	"	33 000	80 000	106 000
"	"	89 678	"	32 400	80 000	110 100
Box	"	13 664	W. C.	29 000	60 000	32 100
Refrigerator	"	55 059	I. C.	36 900	60 000	38 400
Box	E	14 010	N. Y. C.	33 600	30 000	31 000
"	L	21 307	I. C.	37 500	80 000	56 300
"	E	41 633	P. M.	34 500	60 000	35 600
"	L	18 103	C. B. & Q.	25 200	40 000	64 000
"	"	131 327	I. C.	39 700	80 000	91 400
"	"	122 440	C. S, N. O. & P.	39 500	80 000	109 100
"	"	8 116	St. J. & G. I.	35 400	80 000	73 800
"	"	39 116	I. C.	36 300	80 000	111 600
"	"	141 137	"	43 100	100 000	64 300
"	"	12 971	"	30 200	60 000	46 000
"	"	7 198	Big Four	31 200	60 000	93 500
"	"	19 591	M. & O.	33 700	60 000	88 200
"	"	18 581	"	33 500	60 000	91 500
"	"	9 593	"	31 200	60 000	83 600
"	"	9 224	C. I. & L.	29 800	50 000	73 100
"	"	11 136	M. C. & St. L.	34 000	60 000	67 700
"	E	64 614	C. & N. W.	30 100	60 000	29 400
"	L	5 251	N. C. & St. L.	29 500	60 000	93 400
"	"	6 714	"	29 600	60 000	69 800
"	"	49 041	I. C.	39 100	80 000	106 800
Gondola	"	95 823	"	31 600	80 000	74 000
Refrigerator	E	5 773	Armour	38 700	50 000	39 600
Box	L	6 692	I. C.	26 800	50 000	72 000
"	"	6 609	T. St. L. & W.	38 100	80 000	82 100
"	"	28 434	N. Y. C.	35 800	80 000	81 000
"	"	14 257	Penn.	44 400	100 000	98 000
"	"	40 571	M. & O.	34 600	60 000	90 000
Gondola	"	85 836	I. C.	30 500	80 000	60 000
Box	"	11 615	"	29 800	60 000	111 000
"	"	13 534	Q. & C.	33 800	60 000	80 000
"	"	42 169	I. C.	33 400	60 000	76 100
"	E	27 093	L. S. & M. S.	29 300	60 000	29 000
"	L	10 859	I. C.	30 000	60 000	66 400
"	"	141 286	"	42 600	100 000	106 200
Gondola	"	3 218	I. S.	40 300	100 000	91 400
Box	"	13 675	I. C.	29 800	60 000	46 000
Gondola	"	93 300	"	31 900	80 000	74 100
Refrigerator	E	55 987	"	38 600	60 000	39 400
Caboose	"	98 040	"			40 000

TABLE 19 Tonnage Record

Test No. S-1038

Kind of Car	Loaded or Empty	Car No.	Car Initial	Stenciled Light Weight	Capacity	Gross Weight
	L. or E.			pounds	pounds	pounds
Test	E	17				58 000
Gondola	L	91 059	I. C.	29 400	80 000	115 000
"	"	106 262	"	40 300	100 000	136 000
"	"	106 565	"	40 300	100 000	134 000
Box	"	142 548	"	42 900	100 000	91 800
Gondola	"	730	C. C. & Co.	30 900	80 000	103 300
"	"	84 047	I. C.	28 500	60 000	85 300
"	"	88 999	"	32 200	80 000	105 000
"	"	85 215	"	31 600	80 000	102 700
"	"	82 640	"	27 600	60 000	81 300
"	"	81 883	"	28 800	60 000	80 000
"	"	76 477	"	23 300	50 000	75 500
"	"	93 590	"	29 800	80 000	107 300
"	"	90 934	"	31 000	80 000	104 800
"	"	93 342	"	32 500	80 000	104 500
"	"	102 091	"	37 300	80 000	120 000
"	"	31 063	C. & O.	39 200	100 000	138 000
"	"	85 304	I. C.	31 500	80 000	111 500
"	"	26 505	C. & O.	38 100	100 000	130 200
"	"	110 803	I. C.	41 100	100 000	135 500
"	"	104 015	"	40 500	100 000	146 500
"	"	105 581	"	40 400	100 000	139 000
"	"	104 984	"	40 500	100 000	146 100
"	"	91 126	"	30 600	80 000	104 000
"	"	88 342	"	31 800	80 000	105 000
"	"	93 901	"	31 500	80 000	103 400
"	"	81 303	"	28 100	60 000	85 000
"	"	44 086	N. & W.	38 300	100 000	129 300
"	"	104 532	I. C.	40 600	100 000	142 300
"	"	15 820	M. & O.	34 100	80 000	104 600
"	"	106 646	I. C.	40 400	100 000	143 800
"	"	88 819	"	31 600	80 000	104 600
"	"	104 584	"	40 400	100 000	152 000
"	"	3 160	I. S.	40 300	100 000	154 000
Box	"	87 344	B. & O.	30 400		73 300
"	"	704	W. H. & D.		60 000	41 000
"	E	12 694	W. C.	29 100	60 000	28 900
"	L	19 705	I. C.	29 600	60 000	74 300
"	"	16 310	"	29 800	60 000	59 600
"	"	12 417	"	29 900	60 000	91 400
Caboose	E	98 090	"			40 000

TABLE 20 Tonnage Record

Test No. S-1040

Kind of Car	Loaded or Empty	Car No.	Car Initial	Stenciled Light Weight	Capacity	Gross Weight
	L. or E.			pounds	pounds	pounds
Test	E	17				58 000
Box	L	98 633	C. B. & Q.	34 300	80 000	54 900
Gondola	"	106 306	I. C.	40 800	100 000	138 500
"	"	106 368	"	40 400	100 000	146 500
"	"	94 314	"	29 000	80 000	105 600
Box	"	39 814	"	37 100	80 000	121 000
Gondola	"	86 947	"	31 100	80 000	110 000
"	"	16 683	H. V. Y.	32 800	80 000	110 700
"	"	97 659	I, C.	30 200	80 000	99 300
Box	"	78 121	B. & O.	31 600	60 000	70 200
Gondola	"	90 363	I. C.	33 600	80 000	95 600
"	"	13 381	N. & W.	34 100	80 000	107 600
Box	"	35 061	St. L. & S. F.	35 100	60 000	82 200
"	"	17 339	I. C.	28 600	60 000	62 000
"	"	37 489	"	33 500	80 000	71 200
Tank	"	505	F. O. Co.		60 000	88 900
Box	"	25 394	V. S. & P	32 200	60 000	80 400
"	"	131 417	I. C.	39 900	80 000	64 500
"	"	39 626	"	36 200	80 000	79 000
Gondola	"	92 487	"	30 000	80 000	110 600
Box	"	91 157	L, & N.	33 200	65 000	86 500
Gondola	"	89 843	I. C.	30 900	80 000	86 600
Box	"	4 931	N. & S.	32 200	60 000	74 300
Gondola	"	5 642	K. & M.	32 500	80 000	91 600
"	"	93 209	I. C.	32 800	80 000	110 000
Box	"	34 736	"	36 400	80 000	56 300
"	"	101 264	C. B. & Q.	35 000	80 000	60 000
"	"	32 412	C. R. I. & P.	38 900	80 000	67 900
"	"	10 137	N. C. & St. L.	33 400	80 000	80 300
Gondola	"	94 256	I. C.	30 000	80 000	78 800
Box	"	3 467	L. E. & St. L.	34 300	60 000	101 000
"	"	11 192	S.	30 900	60 000	75 800
"	"	46 541	I. C.	38 000	80 000	67 100
Gondola	"	86 513	"	31 200	80 000	125 800
"	"	89 288	"	31 800	80 000	95 800
"	"	105 949	"	40 300	100 000	145 600
"	"	91 129	"	28 800	80 000	108 100
"	"	85 020	"	31 400	80 000	108 900
"	"	95 929	"	29 900	80 000	124 000
"	"	12 555	C. & O.	30 900	80 000	115 800
"	"	96 796	I. C.	31 900	100 000	114 300
"	"	84 200	"	27 400	60 000	80 000
"	"	27 738	H. V.	40 700	100 000	147 900
Box	"	30 778	S. P.	34 000	80 000	85 200
"	"	49 450	I. C.	35 300	80 000	67 700
"	"	17 968	"	31 200	80 000	52 300
Caboose	E		"			40 000

TABLE 21 TONNAGE RECORD

Test No. S-1043

Kind of Car	Loaded or Empty	Car No.	Car Initial	Stenciled Light Weight	Capacity	Gross Weight
	L. or E.			pounds	pounds	pounds
Gondola	E	95 986	I. C.	30 600	80 000	30 600
"	"	101 110	"	38 400	100 000	38 400
"	"	5 968	P. & L. E.	34 300	80 000	34 300
Box	"	37 982	I. C.	37 300	80 000	37 300
"	"	15 601	"	29 300	60 000	29 300
"	"	19 314	"	29 900	60 000	29 900
"	"	12 938	"	29 600	60 000	29 600
"	"	17 905	"	30 100	60 000	30 100
"	"	14 809	"	30 400	60 000	30 400
"	"	37 132	"	33 000	80 000	33 000
"	"	11 765	"	29 900	60 000	29 900
"	"	23 243	"	33 800	80 000	33 800
"	"	41 230	"	32 900	50 000	32 900
"	"	37 957	"	33 000	80 000	33 000
"	"	35 762	"	35 600	80 000	35 600
"	"	36 298	"	36 400	80 000	36 400
"	"	15 281	"	30 400	60 000	30 400
Tank	L	489	A. T. L.	38 000	65 000	102 900
Gondola	E	643	C. C. & C.	31 700	80 000	31 700
"	"	641	"	31 700	80 000	31 700
"	"	182 400	C. I. & S.	31 000	80 000	31 000
"	"	82 014	I. C.	26 500	60 000	26 500
"	"	638	C. C. & C.	31 700	80 000	31 700
"	"	19 570	C. & A.	37 200	100 000	37 200
"	"	89 865	I. C.	31 700	80 000	31 700
"	"	105 764	"	40 400	100 000	40 400
"	"	92 517	"	32 000	80 000	32 000
"	"	3 303	I. S.	40 200	100 000	40 200
"	"	97 056	I. C.	32 500	100 000	32 500
"	"	83 510	"	28 400	60 000	28 400
"	"	97 836	"	30 900	80 000	30 900
"	"	89 837	"	32 200	80 000	32 200
"	"	81 684	"	30 700	60 000	30 700
"	"	115 302	"	42 600	100 000	42 600
"	"	81 483	"	28 000	60 000	28 000
"	"	87 171	"	31 500	80 000	31 500
"	"	25 359	P & R.	33 200	100 000	31 200
"	"	95 635	I. C.	30 200	80 000	30 200
"	"	92 911	"	31 200	80 000	31 200
"	"	88 752	"	32 000	80 000	32 000
"	"	25 900	H. V.	33 100	80 000	33 100
"	"	85 502	I. C.	31 500	80 000	31 500
"	"	89 559	"	31 900	80 000	31 200
"	"	93 107	"	31 800	80 000	31 800
"	"	81 999	"	28 300	60 000	28 700
"	"	104 780	"	40 300	100 000	40 300
"	"	93 305	"	31 200	80 000	31 200
"	"	110 801	"	41 100	100 000	41 100
"	"	97 203	"	30 200	100 000	30 200
"	"	93 068	"	31 200	80 000	31 200
"	"	91 183	"	30 900	80 000	30 000
"	"	86 323	"	30 100	80 000	30 100
"	"	85 904	"	31 600	80 000	31 600
"	"	95 984	"		80 000	32 100
"	"	93 093	"	32 000	80 000	32 000
"	"	89 480	"	30 800	80 000	30 800
"	"	111 066	"	41 100	100 000	41 100
"	"	111 012	"	41 200	100 000	41 900
"	"	97 889	"	31 400	80 000	31 400
"	"	96 577	"	32 400	100 000	32 400
"	"	97 927	"	32 000	80 000	32 000
"	"	90 488	"	30 600	80 000	30 600
"	"	9 548	T. & O. C.	26 300	60 000	26 300
"	"	111 311	I. C.	40 800	100 000	40 800
Box	"	6 498	N. C. & St. L.	29 200	60 000	29 200
Caboose	"	98 185	I. C.	40 000		40 000

TABLE 22 TONNAGE RECORD

Test No. S-1048

Kind of Car	Loaded or Empty	Car No.	Car Initial	Stenciled Light Weight	Capacity	Gross Weight
	L. or E.			pounds	pounds	pounds
Test	E	17				58 000
Box	L	98 252	N. Y. C.&H. R.	35 600	80 000	43 500
Gondola	"	106 449	I. C.	40 300	100 000	140 000
"	"	18 867	C. H. & D.	30 200	70 000	97 200
"	"	15 342	C. & O.	30 700	85 000	78 300
"	"	104 271	I. C.	40 600	100 000	146 500
"	"	68 282	L. & N.	36 800	80 000	120 000
"	"	10 579	I. C.	41 200	100 000	134 300
"	"	83 518	"	27 000	60 000	82 600
"	"	95 129	"	31 200	80 000	107 900
"	"	93 198	"	30 600	80 000	105 000
"	"	96 507	"	32 300	100 000	111 000
"	"	93 807	"	29 300	80 000	107 800
"	"	106 189	"	40 400	100 000	142 100
"	"	111 300	"	40 800	100 000	124 200
"	"	105 618	"	40 300	100 000	106 600
"	"	91 108	"	29 900	80 000	108 500
Box	"	2 059	C. P. T.	30 800	60 000	90 800
Gondola	"	84 458	I. C.	30 800	60 000	92 400
"	"	87 958	"	31 800	80 000	109 000
"	"	295 924	P.	40 800	100 000	125 400
"	"	28 318	C & O		100 000	144 200
"	"	82 790	I. C.	31 400	60 000	86 400
"	"	86 569	"	30 600	80 000	107 700
"	"	87 485	"	33 000	80 000	108 600
"	"	94 069	"	31 000	80 000	107 400
"	"	89 271	"	32 000	80 000	109 200
"	"	81 366	"	29 100	60 000	84 200
"	"	95 850	"	30 500	80 000	104 600
"	"	110 910	"	40 800	100 000	140 800
"	"	96 255	"	31 000	80 000	105 000
"	"	94 541	"	31 400	80 000	107 600
"	"	83 229	"	27 000	60 000	85 000
"	"	95 820	"	30 800	80 000	100 000
"	"	82 045	"	28 900	60 000	87 300
"	"	94 443	"	30 300	80 000	105 300
"	"	106 431	"	40 400	100 000	121 600
Box	"	16 036	"	30 800	60 000	80 400
"	E	6 672	A. R. L.	31 500	50 000	33 600
"	"	5 284	"	32 800	50 000	39 400
"	"	9 851	"	39 400	50 000	39 800
"	"	7 342	S.			39 500
"	"	10 458	A.	39 500	60 000	39 600
"	L	8 969	A. R. L.	34 000	50 000	42 100
"	E	352	U. R. T.	42 000	50 000	47 300
"	L	141 533	I. C.	43 700	100 000	96 600
"	"	66 182	C. & N. W.	30 000	60 000	65 300
"	"	28 208	I. C.	35 500	60 000	68 500
"	"	13 088	C. G. W.	30 000	60 000	58 700
"	"	16 008	C. B.	32 000	60 000	58 500
"	"	41 753	P. M.	36 700	60 000	64 300
"	"	13 494	I. C.	31 100	60 000	72 200
"	"	19 247	"	29 600	60 000	63 900
Caboose	E	98 098	"			40 000

TABLE 23 Tonnage Record

Test No. S–1050

Kind of Car	Loaded or Empty	Car No.	Car Initial	Stenciled Light Weight	Capacity	Gross Weight
	L. or E.			pounds	pounds	pounds
Box	L	34 403	I. C.	36 800	80 000	124 900
"	"	13 317	"	30 100	60 000	81 000
"	"	11 385	"	29 200	60 000	91 800
"	"	140 166	"	42 800	100 000	139 500
"	"	42 477	"	34 400	60 000	84 200
"	"	36 731	"	33 700	80 000	100 900
"	"	39 317	"	37 500	80 000	125 200
"	"	25 435	"	36 600	80 000	119 500
"	E	31 909	T. R. E.	32 100	50 000	34 800
"	L	25 238	I. C.	36 900	80 000	119 300
"	"	45 799	"	41 400	80 000	105 200
"	E	12 043	O. N. & T. P.	33 550	60 000	33 500
"	L	36 163	I. C.	36 800	80 000	121 600
"	"	24 790	"	35 800	80 000	120 800
"	"	6 364	"	27 600	50 000	82 400
"	"	14 070	"	31 600	60 000	100 300
"	"	15 686	"	30 300	60 000	97 000
"	"	35 619	"	36 500	80 000	126 800
"	"	15 962	"	30 400	60 000	88 800
"	"	141 521	"	43 600	100 000	142 400
"	"	130 492	"	40 100	80 000	120 800
"	"	45 566	"	38 500	80 000	119 900
"	"	131 556	"	39 000	80 000	97 600
"	"	21 716	"	37 800	80 000	105 600
"	"	46 134	"	40 700	80 000	127 700
"	"	39 374	"	37 900	80 000	125 200
"	E	31 415	T. R. E.	32 400	50 000	32 400
"	"	31 968	"	32 100	50 000	33 000
"	"	31 395	"	34 100	50 000	34 800
Gondola	"	94 837	I. C.	32 800	80 000	32 800
"	"	110 177	"	41 200	100 000	41 200
"	"	3 170	I. S.	38 200	100 000	38 200
"	"	91 705	I. C.	29 700	80 000	29 700
"	"	90 682	"	30 700	80 000	30 700
"	"	86 138	"	30 100	80 000	30 100
"	"	104 284	"	40 700	100 000	40 700
"	"	104 495	"	40 700	100 000	40 700
"	"	107 359	"	39 600	100 000	39 600
"	"	110 117	"	41 700	100 000	41 700
Caboose	"	98 197	"			34 000

TABLE 24 Tonnage Record

Test No. S-1052

Kind of Car	Loaded or Empty	Car No.	Car Initial	Stenciled Light Weight	Capacity	Gross Weight
	L. or E.			pounds	pounds	pounds
Gondola	E	91 208	I. C.	30 200	80 000	30 200
"	"	83 764	"	26 800	60 000	26 800
"	"	252	S. S. C.	25 500	50 000	25 800
"	"	89 137	I. C.	31 200	80 000	31 300
"	"	83 992	"	28 200	60 000	28 400
"	"	112 770	"	43 500	100 000	43 500
"	"	81 989	"	28 900	50 000	28 900
"	"	94 688	"	31 100	80 000	31 300
"	"	101 073	"	38 200	100 000	38 200
"	"	3 351	I. S.	40 700	100 000	40 800
"	"	106 100	I. C.	40 200	100 000	40 200
"	"	106 314	"	40 300	100 000	40 200
"	"	82 600	"	26 800	60 000	27 000
"	"	91 316	"	30 200	80 000	30 500
"	"	722	C. C. & Co.	31 700	80 000	31 200
"	"	91 162	I. C.	29 700	80 000	30 100
"	"	107 030	"	39 800	100 000	39 800
"	"	641	C. C. & Co.	31 700	80 000	31 500
"	"	80 993	I. C.	23 600	60 000	26 500
Box	"	11 116	F. G. E.	36 500	50 000	33 200
"	"	11 050	"	36 500	50 000	34 600
"	"	31 153	T. R. E.	32 300	50 000	34 000
"	"	31 286	"	31 500	50 000	34 200
"	"	11 243	N. C. & St. L.	33 600	60 000	33 500
"	"	15 945	Air Line	34 600	60 000	34 800
"	"	827	D. S. D.	35 500	50 000	37 800
"	"	133 280	S.	33 500	60 000	32 800
"	"	33 886	C. of N. J.	30 500	60 000	30 600
"	L	24 968	I. C.	36 000	80 000	119 500
"	"	39 671	"	36 300	80 000	118 100
"	"	21 633	"	38 400	80 000	122 500
"	"	131 151	"	38 900	80 000	129 600
"	"	13 792	"	29 800	60 000	92 300
"	"	45 456	"	38 800	80 000	98 000
"	"	47 105	"	40 100	80 000	100 200
"	"	20 336	"	28 600	60 000	89 000
"	"	13 831	"	29 900	60 000	89 000
"	E	25 361	V. S. & P.	31 800	60 000	31 800
"	"	31 199	T. R. E.	32 150	50 000	34 800
"	"	30 283	"	38 700	50 000	36 000
Gondola	L	92 708	I. C.	32 000	80 000	84 000
"	"	112 608	"	43 500	100 000	88 400
Box	"	580 498	U. L.	30 500	60 000	53 500
"	E	30 562	S.	35 600	60 000	35 400
Gondola	L	92 748	I. C.	30 400	80 000	74 000
Box	E	25 391	V. S. & P.	32 200	60 000	32 400
"	"	17 212	L. & N.	31 200	60 000	31 700
"	"	35 863	S.	35 900	60 000	35 800
"	"	37 798	S.	35 200	60 000	35 800
"	L	130 809	I. C.	40 200	80 000	97 800
Gondola	"	94 511	"	31 000	80 000	37 800
Box	"	141 249	"	43 500	100 000	82 800
"	"	39 219	"	36 300	80 000	79 000
"	E	25 618	A. C. L.	34 960	60 000	34 700
"	"	19 314	St. L. S. W.	32 700	60 000	32 800
"	"	85 683	S. P.	42 600	100 000	43 500
"	"	10 255	N. C. & St. L.	32 900	60 000	34 000
"	"	5 803	L. & N.	30 500	60 000	30 000
"	"	20 864	S.	32 800	60 000	35 100
Flat	"	10 016	N. O. & N. E.	27 200	80 000	27 000
Caboose	"	98 093	I. C.			34 000

TABLE 25 Tonnage Record

Test No. S–1057

Kind of Car	Loaded or Empty	Car No.	Car Initial	Stenciled Light Weight	Capacity	Gross Weight
	L or E			pounds	pounds	pounds
Test	E	17				58 000
Box	L	12 269	C. N. O. & T. P.	33 600	60 000	89 300
Gondola	"	91 889	I. C.	29 500	80 000	107 400
"	"	83 859	"	27 200	60 000	87 800
"	"	83 709	"	28 000	60 000	88 200
"	"	94 023	"	30 600	80 000	102 200
"	"	97 927	"	32 000	80 000	100 600
Box	"	46 152	"	40 000	80 000	58 700
Gondola	"	93 980	"	30 700	80 000	105 400
"	"	91 254	"	29 400	80 000	110 800
Box	"	6 750	"	26 400	50 000	68 600
"	E	57 408	N. Y. C. & H. R.	31 000	60 000	36 100
"	L	108 212	Erie	39 900	80 000	69 700
Tank	"	628	D. R. & U.			68 200
Gondola	"	91 422	I. C.	30 000	80 800	105 600
Box	E	D27 572	L. S. & M. S.	28 800	60 000	33 400
"	L	15 891	I. C.	28 700	60 000	70 300
"	"	11 267	"	28 400	60 000	81 100
"	"	33 918	"	37 900	80 000	80 300
Gondola	"	106 527	"	40 200	100 000	142 800
"	"	104 823	"	40 300	100 000	145 100
"	"	91 474	"	29 900	80 000	112 800
"	"	82 786	"	26 900	60 000	86 700
"	"	607	C. C. & C.	31 700	80 000	107 800
"	"	106 577	I. C	40 300	100 000	144 400
"	"	106 447	"	40 400	100 000	142 900
Box	"	130 255	"	41 000	80 000	90 300
"	"	7 086	"	26 600	50 000	69 000
Flat	"	67 554	"	28 800	80 000	56 200
Box	"	39 223	"	37 500	80 000	72 800
"	"	21 181	"	37 500	80 000	85 800
"	E	515 733	P. F. W. C.	43 800	100 000	41 200
"	L	29 516	I. C.	39 800	60 000	73 000
Flat	"	2 292	G. C.	23 500	60 000	79 200
Gondola	"	105 859	I. C.	40 400	100 000	146 200
"	"	86 778	"	31 000	80 000	115 100
"	"	112 241	"	36 500	80 000	96 300
Box	"	15 982	"	30 400	60 000	80 000
Gondola	E	189	C. & I. W.	32 700	90 000	33 100
"	"	7 162	N. Y. C. & St. L.	31 700	80 000	31 000
"	L	91 371	I. C.	30 400	80 000	80 600
Flat	"	814	G. & S. I.	26 600	80 000	85 800
Box	"	15 282	I. C.	29 400	60 000	67 400
"	E	1 695	A. R.	28 200	50 000	31 200
"	L	15 427	I. C.	30 000	60 000	67 800
"	"	24 933	"	35 000	80 000	102 000
"	"	27 737	B.	29 500	60 000	61 200
"	"	40 712	M. & O.	34 500	60 000	72 800
Gondola	"	85 879	I. C.	30 500	80 000	79 600
Box	"	36 585	"	36 000	80 000	58 200
Caboose	E	98 565	"			34 000

TABLE 26 TONNAGE RECORD

Test No. S-1061

Kind of Car	Loaded or Empty	Car No.	Car Initial	Stenciled Light Weight	Capacity	Gross Weight
	L or E			pounds	pounds	pounds
Test	E	17				58 000
Gondola	L	88 518	I. C.	32 200	80 000	107 400
"	"	106 156	"	38 400	100 000	146 000
"	"	106 707	"	40 500	100 000	144 600
"	"	94 475	"	31 100	80 000	109 200
"	"	81 333	"	27 300	60 000	82 300
"	"	86 360	"	31 900	80 000	104 300
"	"	95 040	"	30 400	80 000	106 600
"	"	101 029	"	37 500	100 000	138 600
"	"	112 734	"	43 500	100 000	112 600
"	"	81 632	"	26 200	60 000	85 200
"	"	87 626	"	31 700	80 000	103 700
"	"	80 610	"	27 200	60 000	82 400
"	"	94 976	"	31 400	80 000	119 000
"	"	88 425	"	31 400	80 000	118 000
"	"	95 299	"	30 500	80 000	101 200
"	"	628	C. C. & Co.	31 700	80 000	110 400
"	"	95 250	I. C.	30 300	80 000	112 000
"	"	88 750	"	31 900	80 000	112 200
"	"	276	S. C. Co.	30 700	80 000	112 000
"	"	205	S. S. C. Co.	26 500	60 000	82 700
"	"	254	"	26 500	50 000	80 000
"	"	208	"	26 500	60 000	81 300
"	"	256	"	25 500	50 000	80 000
"	"	88 256	I. C.	32 000	80 000	107 700
"	"	104 074	"	40 600	100 000	138 400
"	"	93 754	"	29 600	80 000	104 400
"	"	92 486	"	30 500	80 000	102 000
"	"	106 300	"	40 200	100 000	147 300
"	"	104 742	"	40 300	100 000	146 000
"	"	106 846	"	40 500	100 000	141 000
"	"	11 247	"	40 900	100 000	134 900
"	"	111 175	"	40 700	100 000	136 900
"	"	84 467	"	30 400	60 000	96 200
"	"	90 399	"	31 000	80 000	108 600
"	"	82 953	"	28 000	60 000	91 200
"	"	86 147	"	31 200	80 000	103 500
"	"	107 646	"	39 500	100 000	137 900
Flat	"	6 708	"	27 900	60 000	81 800
"	E	3 736	A. C. L.	31 700	40 000	31 700
"	L	6 719	"	27 900	60 000	74 400
"	"	6 455	"	26 400	60 000	66 400
"	E	8 494	H. & H.	28 800	80 000	30 300
Caboose	"	98 155	I. C.			34 000

TABLE 27 TONNAGE RECORD

Test No. S-1063

Kind of Car	Loaded or Empty	Car No.	Car Intial	Stenciled Light Weight	Capacity	Gross Weight
	L or E			pounds	pounds	pounds
Box	L	22 195	I. C.	37 800	80 000	115 400
"	"	46 472	"	36 500	80 000	127 300
"	"	17 530	"	28 600	60 000	95 200
"	"	49 063	"	37 200	80 000	125 300
Gondola	E	112 486	"	43 400	100 000	43 400
"	"	112 463	"	43 700	100 000	43 700
"	"	112 300	"	36 500	80 000	36 500
"	"	112 527	"	43 400	100 000	43 400
"	"	112 515	"	43 500	100 000	43 500
"	"	112 428	"	43 300	100 000	43 300
"	"	112 407	"	43 600	100 000	43 600
"	"	112 679	"	43 300	100 000	43 300
"	"	112 403	"	43 500	100 000	43 500
"	"	112 775	"	43 600	100 000	43 600
"	"	112 585	"	43 400	100 000	43 400
"	"	92 756	"	30 500	80 000	30 500
"	"	88 647	"	31 500	80 000	31 500
"	"	82 152	"	26 600	60 000	26 600
"	"	112 633	"	43 500	100 000	43 500
"	"	112 578	"	43 400	100 000	43 400
"	"	112 596	"	43 700	100 000	43 700
"	"	112 685	"	43 600	100 000	43 600
"	"	112 549	"	43 400	100 000	43 400
"	"	112 502	"	43 400	100 000	43 400
"	"	112 724	"	43 500	100 000	43 500
"	"	112 481	"	43 200	100 000	43 200
"	"	112 709	"	43 400	100 000	43 400
"	"	112 494	"	43 800	100 000	43 800
"	"	112 684	"	43 600	100 000	43 600
"	"	106 653	"	40 300	100 000	40 300
"	"	87 789	"	31 300	80 000	31 300
"	"	82 875	"	28 400	60 000	28 400
"	"	95 097	"	30 200	80 000	30 200
"	"	92 650	"	30 000	80 000	30 000
"	"	93 464	"	30 000	80 000	30 000
"	"	89 101	"	31 600	80 000	31 600
"	"	90 956	"	31 400	80 000	31 400
"	"	86 615	"	30 500	80 000	30 500
"	"	96 487	"	30 600	80 000	30 600
"	"	110 780	"	41 000	100 000	41 000
"	"	86 267	"	31 200	80 000	31 200
"	"	111 294	"	41 100	100 000	41 100
"	"	95 713	"	32 700	80 000	32 700
"	"	88 462	"	32 200	80 000	32 200
"	"	88 685	"	30 800	80 000	30 800
"	"	81 090	"	27 200	60 000	27 200
"	"	81 497	"	29 100	60 000	29 100
"	"	107 342	"	39 500	100 000	39 500
"	"	90 418	"	31 200	80 000	31 200
"	"	80 286	"	26 200	60 000	26 200
"	"	75 883	"	27 600	50 000	27 600
"	"	87 257	"	26 700	60 000	26 700
"	"	104 716	"	39 500	100 000	39 500
"	"	80 963	"	28 200	60 000	28 200
"	"	88 848	"	32 300	80 000	32 300
"	"	95 991	"	30 500	80 000	30 500
"	"	112 072	"	35 900	80 000	35 900
"	"	89 296	"	32 800	80 000	32 800
"	"	87 877	"	31 000	80 000	31 000
"	"	90 809	"	30 000	80 000	30 000
"	"	91 004	"	30 500	80 000	30 500
"	"	96 718	"	31 600	100 000	31 600
"	"	95 836	"	32 000	80 000	32 000
"	"	87 904	"	32 000	80 000	32 000
"	"	95 513	"	30 800	80 000	30 800
"	"	106 236	"	40 400	100 000	40 400
"	"	97 033	"	33 500	100 000	33 500
"	"	110 743	"	41 100	100 000	41 100
"	"	112 512	"	43 400	100 000	43 400
"	"	110 531	"	40 600	100 000	40 600
"	"	88 994	"	31 300	80 000	31 300
"	"	85 921	"	31 800	80 000	31 800
"	"	70 984	"	23 300	40 000	23 300
Caboose	"	98 068	"			34 000

TABLE 28 TONNAGE RECORD

Test No. S–1070

Kind of Car	Loaded or Empty	Car No.	Car Initial	Stenciled Light Weight	Capacity	Gross Weight
	L or E			pounds	pounds	pounds
Test	E	17				58 000
Box	L	10 826	I. C.	31 300	60 000	96 800
"	"	131 644	"	39 600	80 000	127 100
"	E	25 703	V. S. & P.	32 000	60 000	32 000
"	L	7 628	I. C.	27 200	50 000	91 000
"	"	12 951	"	29 700		99 800
"	"	33 524	"	36 500	80 000	120 100
"	"	22 113	"	40 200	80 000	93 900
Gondola	"	97 293	"	31 500	100 000	78 500
"	"	96 803	"	34 400	100 000	74 900
Stock	E	151 427	"		40 000	29 300
"	"	150 457	"		40 000	28 100
"	"	32 589	"	31 200	60 000	31 200
"	"	32 738	"	31 000	60 000	31 000
"	"	150 986	"	30 000	40 000	30 000
"	"	4 206	S. W. S. C. L.	29 300	40 000	29 300
"	"	32 714	I. C.	33 200	60 000	33 200
"	"	151 275	"	29 600	40 000	29 800
"	"	32 663	"	32 600	60 000	32 600
"	"	31 168	"	29 000	50 000	29 700
"	"	150 874	"	32 800	60 000	32 600
"	"	32 176	"	32 800	60 000	32 800
"	"	151 497	"	31 100	40 000	31 100
"	"	151 023	"	30 300	40 000	30 300
"	"	32 411	"	35 000	60 000	35 000
Box	L	142 729	"	42 900	100 000	65 200
"	"	39 777	"	37 400	80 000	61 100
"	"	19 989	"	28 300	60 000	60 900
"	E	95 571	L. & N.	34 500	65 000	34 500
"	L	140 687	I. C.	42 700	100 000	137 600
"	"	45 487	"	38 400	80 000	119 600
"	"	142 979	"	42 800	100 000	136 900
"	"	142 275	"	42 700	100 000	135 000
"	E	30 047	T. R. E.	34 800	50 000	34 800
"	"	31 974	"	32 100	50 000	32 100
Gondola	"	95 202	I. C.	30 400	80 000	31 400
"	"	96 724	"	32 000	100 000	32 000
"	"	106 393	"	40 400	100 000	40 400
"	"	87 275	"	32 200	80 000	33 200
Box	L	15 680	"	29 900	60 000	91 200
Gondola	E	96 130	"	32 000	80 000	32 000
Box	"	55 803	"	37 700	60 000	37 700
"	"	21 244	F. G. E.	36 500	50 000	36 500
Gondola	"	82 606	I. C.	27 500	60 000	27 500
"	"	82 709	"	28 800	60 000	28 800
Box	L	135 028	S.	33 700	60 000	68 700
Gondola	E	88 465	I. C.	32 600	80 000	32 600
"	"	91 623	"	30 700	80 000	30 700
"	"	106 662	"	40 000	100 000	40 000
"	"	86 231	"	31 700	80 000	31 700
"	"	80 430	"	26 500	60 000	26 500
"	"	93 350	"	31 300	80 000	31 300
"	"	94 475	"	31 100	80 000	31 100
"	"	93 620	"	30 400	80 000	30 400
"	"	96 757	"	31 800	100 000	31 800
"	"	89 088	"	30 200	80 000	30 200
"	"	82 367	"	26 800	60 000	26 800
"	"	94 594	"	30 300	80 000	30 300
"	"	92 570	"	31 000	80 000	31 000
"	"	115 109	"	43 000	100 000	43 000
"	"	81 261	"	29 000	60 000	29 000
"	"	84 172	"	28 400	60 000	28 400
"	"	83 919	"	28 200	60 000	28 200
"	"	714	C. C.C. & Co.	31 800	80 000	31 800
"	"	92 158	I. C.	30 400	80 000	30 400
Caboose	"	98 130	"			34 000

TABLE 29 TONNAGE RECORD

Test No. S-1072

Kind of Car	Loaded or Empty	Car No.	Car Initial	Stenciled Light Weight	Capacity	Gross Weight
	L or E			pounds	pounds	pounds
Gondola	L	106 825	I. C.	40 400	100 000	134 700
"	"	104 661	"	40 300	100 000	146 700
"	"	106 529	"	40 200	100 000	144 900
"	"	104 968	"	39 200	100 000	144 700
"	"	115 250	"	42 700	100 000	141 900
"	"	111 111	"	40 900	100 000	148 300
"	"	89 762	"	31 600	80 000	114 200
"	"	110 559	"	40 800	100 000	147 600
"	"	86 636	"	31 200	80 000	114 100
"	"	107 020	"	39 800	100 000	144 300
"	"	91 917	"	30 800	80 000	114 000
"	"	87 078	"	31 800	80 000	117 900
"	"	110 980	"	41 600	100 000	144 000
"	"	110 318	"	40 900	100 000	137 800
"	"	106 382	"	40 400	100 000	136 900
"	"	107 436	"	39 700	100 000	147 600
"	"	91 606	"	30 400	80 000	114 100
"	"	101 156	"			159 100
"	"	101 075	"		100 000	120 100
"	"	106 878	"	40 200	100 000	144 900
"	"	102 054	"	38 000	80 000	117 000
"	"	110 951	"	41 800	100 000	131 000
"	"	105 669	"	40 200	100 000	139 200
"	"	3 345	I. S.	40 100	100 000	147 700
"	"	105 713	I. C.	39 800	100 000	143 900
"	"	106 629	"	40 300	100 000	142 100
"	"	106 121	"	40 400	100 000	144 100
Caboose	E	98 155	"			35 100

TABLE 30 TONNAGE RECORD

Test No. S-1073

Kind of Car	Loaded or Empty	Car No.	Car Initial	Stenciled Light Weight	Capacity	Gross Weight
	L or E			pounds	pounds	pounds
Gondola	L	104 181	I. C.	40 800	100 000	139 300
"	"	110 059	"	42 300	100 000	135 800
"	"	110 679	"	42 000	100 000	135 700
"	"	111 062	"	41 000	100 000	134 500
"	"	111 336	"	40 100	100 000	134 300
"	"	112 464	"	43 400	100 000	118 600
"	"	112 431	"	43 300	100 000	118 700
"	"	106 038	"	38 800	100 000	133 700
"	"	107 581	"	40 100	100 000	130 200
"	"	3 012	I. S.	40 100	100 000	145 200
"	"	115 335	I. C.	43 000	100 000	141 600
"	"	106 459	"	40 000	100 000	138 800
"	"	3 400	I. S.	40 400	100 000	141 700
"	"	106 818	I. C.	40 500	100 000	141 200
"	"	106 087	"	41 200	100 000	141 900
"	"	3 131	I. S.	40 200	100 000	141 400
"	"	104 817	I. C.	40 400	100 000	141 800
"	"	107 217	"	39 700	100 000	141 300
"	"	107 599	"	39 600	100 000	142 000
"	"	106 101	"	40 300	100 000	141 900
"	"	106 598	"	40 200	100 000	142 500
"	"	106 197	"	40 400	100 000	138 600
"	"	104 390	"	40 700	100 000	140 400
"	"	105 651	"	40 300	100 000	140 600
"	"	106 551	"	40 000	100 000	143 100
"	"	107 124	"	39 600	100 000	140 500
"	"	106 722	"	40 300	100 000	141 300
Caboose	E		"			34 000

TABLE 31 Tonnage Record

Test No. S-1074

Kind of Car	Loaded or Empty	Car No.	Car Initial	Stenciled Light Weight	Capacity	Gross Weight
	L or E			pounds	pounds	pounds
Test	E	17				58 000
Gondola	"	92 451	I. C.	30 100	80 000	30 500
"	"	93 288	"	30 800	80 000	31 500
"	"	705	C. C. C. & Co.	31 300	80 000	31 200
"	"	91 779	I. C.	29 900	80 000	29 400
"	"	83 029	"	28 000	60 000	27 400
"	"	86 841	"	31 000	80 000	31 300
"	"	267	St. L. B. & S.	25 700	60 000	24 600
"	"	83 597	I. C.	27 100	60 000	27 200
"	"	82 261	"	28 300	60 000	27 700
"	"	86 473	"	31 400	80 000	31 000
"	"	94 563	"	30 600	80 000	30 700
"	"	85 327	"	30 400	80 000	32 000
"	"	92 664	"	31 200	80 000	30 500
"	"	87 201	"	32 000	80 000	32 000
"	"	95 260	"	29 800	80 000	29 400
"	"	105 612	"	40 400	100 000	40 400
"	"	93 048	"	31 500	80 000	31 200
"	"	295	St. L. B. & S.	24 000	60 000	24 500
"	"	82 249	I. C.	27 000	60 000	27 000
"	"	86 327	"	30 400	80 000	30 600
"	"	85 482	"	31 500	80 000	31 000
"	"	80 882	"	27 600	60 000	27 600
"	"	106 064	"	40 300	100 000	40 400
"	"	105 883	"	40 400	100 000	40 800
"	"	86 779	"	31 000	80 000	33 900
"	"	93 956	"	30 100	80 000	30 400
"	"	104 389	"	40 800	100 000	40 400
"	"	86 183	"	31 000	80 000	30 700
"	"	81 190	"	27 200	60 000	26 800
"	"	86 470	"	30 600	80 000	30 200
"	"	95 912	"	32 000	80 000	30 800
"	"	91 788	"	30 500	80 000	30 300
"	"	86 132	"	29 500	80 000	30 700
"	"	95 167	"	30 500	80 000	31 500
"	"	107 604	"	39 600	100 000	40 000
"	"	87 657	"	32 000	80 000	32 300
"	"	87 590	"	32 300	80 000	35 200
"	"	89 683	"	31 400	80 000	31 200
"	"	7 555	"	23 400	50 000	22 200
"	"	107 148	"	39 800	100 000	40 300
"	"	104 379	"	40 400	100 000	40 400
"	"	88 351	"	31 500	80 000	31 600
"	"	87 468	"	31 900	80 000	31 500
"	"	101 229	"	38 400	100 000	37 800
"	"	88 120	"	32 000	80 000	31 600
"	"	94 806	"	31 500	80 000	31 500
"	"	95 480	"	31 900	80 000	32 000
"	"	87 780	"	32 100	80 000	31 600
"	"	93 494	"	29 700	80 000	30 000
"	"	90 671	"	30 800	80 000	30 800
"	"	106 167	"	40 300	100 000	40 100
"	"	89 097	"	32 000	80 000	31 600
"	"	96 072	"	31 800	80 000	31 200
"	"	88 686	"	31 500	80 000	31 700
"	"	94 133	"	31 900	80 000	30 600
"	"	93 394	"	30 600	80 000	31 300
"	"	106 088	"	40 400	100 000	40 200
"	"	89 272	"	30 600	80 000	30 800
"	"	94 599	"	30 800	80 000	30 800
"	"	87 595	"	32 100	80 000	31 500
"	"	91 986	"	30 500	80 000	30 000
"	"	92 035	"	31 300	80 000	31 200

TABLE 31 TONNAGE RECORD (*Continued*)

Test No. S-1076

Kind of Car	Loaded or Empty	Car No.	Ca Initial	Stenciled Light Weight	Capacity	Gross Weight
	L or E			pounds	pounds	pounds
Gondola	E	93 848	I. C.	29 500	80 000	29 700
"	"	106 911	"	40 200	100 000	40 200
"	"	105 727	"	40 400	100 000	40 900
"	"	80 466	"	26 700	60 000	26 100
"	"	110 363	"	41 500	100 000	40 800
"	"	80 324	"	25 600	60 000	30 300
"	"	95 278	"	31 000	80 000	30 000
"	"	82 246	"	28 500	60 000	28 200
"	"	106 288	"	39 800	100 000	40 000
"	"	105 836	"	40 300	100 000	40 200
"	"	104 811	"	40 300	100 000	40 200
"	"	3 207	I. S.	40 300	100 000	39 800
"	"	91 420	I. C.	29 200	80 000	29 600
"	"	112 413	"	43 400	100 000	43 200
"	"	90 452	"	29 600	80 000	31 600
"	"	104 047	"	40 800	100 000	40 400
"	"	115 181	"	41 800	100 000	42 300
Caboose	"	98 005	"			32 000

TABLE 32 TONNAGE RECORD

Test No. S-1076

Kind of Car	Loaded or Empty	Car No.	Car Initial	Stenciled Light Weight	Capacity	Gross Weight
	L or E			pounds	pounds	pounds
Gondola	L	104 098	I. C.	41 000	100 000	149 000
"	"	104 679	"	39 200	100 000	146 000
"	"	105 091	"	40 400	100 000	148 600
"	"	105 690	"	40 300	100 000	143 400
"	"	3 344	I. S.	40 000	100 000	143 300
"	"	110 982	I. C.	41 100	100 000	137 000
"	"	104 698	"	40 600	100 000	138 500
"	"	104 023	"	40 600	100 000	142 500
"	"	107 109	"	39 700	100 000	144 000
"	"	104 361	"	40 200	100 000	148 000
"	"	107 310	"	39 700	100 000	146 000
"	"	106 268	"	40 300	100 000	147 000
"	"	104 087	"	40 900	100 000	152 000
"	"	106 161	"	40 600	100 000	146 500
"	"	107 133	"	39 700	100 000	144 900
"	"	106 144	"	40 400	100 000	150 000
"	"	111 280	"	41 600	100 000	139 000
"	"	111 229	"	40 800	100 000	135 300
"	"	110 525	"	41 300	100 000	139 300
"	"	106 713	"	40 500	100 000	143 300
"	"	110 736	"	40 700	100 000	142 000
"	"	110 421	"	43 500	100 000	148 000
"	"	110 843	"	41 200	100 000	142 400
"	"	111 061	"	41 200	100 000	141 000
"	"	107 126	"	39 700	100 000	143 000
Caboose	E	98 320	"			36 100

TABLE 33 TONNAGE RECORD

Test No. S-1077

Kind of Car	Loaded or Empty	Car No.	Car Initial	Stenciled Light Weight	Capacity	Gross Weight
	L. or E.			pounds	pounds	pounds
Test	E	17				58 000
Gondola	L	2 186	L. E. A. & W.	36 200	80 000	120 200
"	"	107 315	I. C.	39 700	100 000	138 800
"	"	106 426	"	40 500	100 000	151 800
"	"	104 103	"	37 600	100 000	153 600
"	"	88 740	"	32 000	80 000	104 600
Box	"	82 474	B. & O.	33 600	60 000	83 600
"	E	33 880	S. P.	42 700	100 000	41 900
"	"	11 238	H. & T. C.	40 200	100 000	42 800
"	L	11 150	D. S. S. & A.	32 400	60 000	73 600
"	E	10 846	N. C. & St. L.	35 400	60 000	35 000
"	E	337	G. & F.	32 500	60 000	31 700
"	"	34 552	I. C.	37 700	80 000	37 000
"	"	140 487	"	41 900	100 000	42 000
"	"	142 394	"	42 900	100 000	42 000
"	"	49 498	"	34 400	80 000	34 500
"	"	131 662	"	39 500	80 000	40 000
"	"	38 755	"	36 600	80 000	36 600
"	"	15 853	N. O. &. N. E.	30 600	60 000	30 600
"	"	9 644	L. & N.	40 800	60 000	40 700
"	"	11 712	"	30 900	60 000	30 700
"	L	15 492	I. C.	30 200	60 000	90 000
"	"	141 573	"	43 500	100 000	63 800
"	"	140 563	"	42 200	100 000	64 500
"	E	10 381	L. & N.	29 800	60 000	29 800
"	"	11 364	S.P.L.A.&S.L	43 500	100 000	43 100
"	"	11 893	N. C. & St. L.	33 400	60 000	33 300
"	"	65 969	S. P.	29 600	60 000	30 300
"	"	93 651	L. & N.	36 500	65 000	35 200
"	"	94 824	"	34 800	65 000	34 000
"	"	13 705	"	30 700	60 000	30 700
"	"	9 312	N. C. & St. L.	32 550	60 000	32 700
"	L	98 561	N. Y. C.& H.R.	35 700	80 000	78 200
"	E	12 887	C. N. O. & T. P.	34 500	60 000	33 400
"	"	4 886	N. & S.	33 600	60 000	32 000
"	"	12 027	N. & M.	37 000	80 000	30 200
"	L	131 675	I. C.	38 900	80 000	110 400
"	"	14 554	"	32 000	60 000	75 500
"	"	10 060	"	31 000	60 000	70 000
"	"	12 724	"	29 300	60 000	76 500
"	"	13 276	St. L. S. W.	32 000	60 000	79 900
"	"	26 615	I. C.	35 800	80 000	90 800
"	"	141 284	"	43 500	00 000	105 900
Gondola	E	618	E. F. D. & Co.	24 200		24 800
"	"	744	C. C. & Co.	31 800	80 000	30 600
"	"	106 729	I. C.	40 400	100 000	40 100
"	"	94 563	"	30 600	80 000	35 800
"	"	112 570	"	43 500	100 000	43 100
"	"	112 153	"	37 200	80 000	39 500
"	"	107 346	"	39 700	100 000	39 900
"	"	105 529	"	40 200	100 000	40 600
"	"	104 361	"	40 200	100 000	40 600
Caboose	"	98 370	"			35 900

TABLE 34 TONNAGE RECORD

Test No. S-1079

Kind of Car	Loaded or Empty	Car No.	Car Initial	Stenciled Light Weight	Capacity	Gross Weight
	L or E			pounds	pounds	pounds
Box	E	11 050	H. & T. C.	42 100	100 000	36 200
"	"	43 031	M. C.	30 700	60 000	30 400
"	"	41 654	C. & N. W.	27 100	40 000	27 700
"	L	31 195	C. R. I. & P.	36 300	80 000	80 800
"	"	15 746	I. C.	29 600	60 000	69 000
"	"	22 691	S. P.	26 600	50 000	70 000
Refrigerator	E	6 696	A. R. L.	35 600	50 000	34 000
Box	L	14 053	I. C.	30 500	60 000	70 400
"	"	33 125	"	36 200	80 000	89 600
"	"	39 747	"	36 200	80 000	72 500
"	"	46 477	"	37 200	80 000	76 000
"	"	30 352	R. I. A. & L.	36 400	80 000	74 000
"	"	131 445	I. C.	39 800	80 000	80 000
"	"	19 385	M. P.	32 000	60 000	62 000
"	"	70 716	B. & O.	30 800	60 000	67 600
"	"	31 563	C. R. I. & P.	38 700	80 000	93 500
"	"	700	H. E. & W. T.	31 700	60 000	80 000
"	"	12 116	Mex. Cent.	30 600	27 500K	86 700
Gondola	"	87 798	I. C.	31 600	80 000	66 400
Box	"	46 057	"	39 400	80 000	80 400
"	"	12 562	"	30 300	60 000	69 600
"	"	131 611	"	39 000	80 000	63 600
"	"	142 973	"	41 000	100 000	80 000
"	"	50 174	C. & G. W.	38 400	60 000	79 000
"	"	34 506	I. C.	37 500	80 000	62 700
Gondola	"	82 347	"	27 300		85 600
Box	"	37 578	"	33 000	80 000	85 000
Refrigerator	E	6 459	M. & Co. R. L.			36 700
Gondola	L	97 161	I. C.	32 700	100 000	86 500
Box	"	14 550	"	29 800	60 000	65 300
Gondola	"	91 822	"	31 000	80 000	97 000
Box	"	15 713	"	29 900	60 000	72 500
Refrigerator	E	4 068	M. F. T. Co.	40 500	60 000	40 400
"	"	5 886	A. R. L.	31 900	50 000	34 000
Box	L	142 042	I. C.	42 900	100 000	83 000
Refrigerator	E	307	U. R. T. Co.	38 000	40 000	39 000
Box	L	131 734	I. C.	39 300	80 000	88 700
Refrigerator	E	3 831	U. R. T. Co.		40 000	36 500
Box	"	74 936	Erie	32 200	60 000	32 400
Refrigerator	"	20 018	F. G. E.	38 700	50 000	33 800
"	"	6 115	A. R. L.	36 500	50 000	37 700
Box	L	85 137	U. P.	39 700	80 000	89 000
Gondola	"	111 101	I. C.	40 500	100 000	78 600
Refrigerator	E	1 840	M. R. D.	37 500	60 000	38 500
Box	L	72 907	Penn.	30 900	60 000	91 000
"	"	25 346	C. B. & Q.	27 400	60 000	70 200
"	"	60 245	S. P.	35 200	60 000	88 500
"	"	64 733	"	29 600	60 000	75 500
"	"	11 771	I. C.	29 500	60 000	65 500
"	"	13 983	K. C. S.	31 600	60 000	82 300
Caboose	E	98 260	I. C.			35 400

TABLE 35 Tonnage Record

Test No. S-1080

Kind of Car	Loaded or Empty	Car No.	Car Initial	Stenciled Light Weight	Capacity	Gross Weight
	L or E			pounds	pounds	pounds
Test	E	17				58 000
Box	L	10 315	I. C.	30 400	60 000	91 200
"	"	141 744	"	43 600	100 000	147 100
"	"	141 622	"	43 600	100 000	135 200
"	"	21 385	"	36 600	80 000	124 200
"	E	31 478	T. R. E.	32 200	50 000	33 400
"	L	38 140	I. C.	34 400	80 000	125 000
"	"	48 223	"	39 800	80 000	89 300
Gondola	E	104 852	"	40 000	100 000	39 400
"	"	105 936	"	40 000	100 000	40 000
"	"	88 440	"	31 600	80 000	31 600
Box	"	12 090	M. L. & T.	32 000	60 000	31 800
Gondola	"	90 647	I. C.	31 500	80 000	31 600
"	"	82 853	"	28 400	60 000	27 900
"	"	107 665	"	39 900	100 000	39 900
"	"	106 701	"	40 600	100 000	40 400
"	"	106 321	"	40 400	100 000	40 200
"	"	3 354	I. S.	40 400	100 000	40 100
"	"	104 969	I. C.	40 000	100 000	40 000
"	"	106 793	"	40 200	100 000	40 100
"	"	101 154	"	37 600	100 000	37 800
"	"	100 021	"	32 700	90 000	33 000
"	"	107 624	"	39 600	100 000	40 000
"	"	107 217	"	39 700	100 000	39 900
"	"	106 305	"	39 400	100 000	40 100
"	"	104 027	"	40 400	100 000	40 500
"	"	94 971	"	33 200	80 000	31 900
"	"	94 209	"	30 600	80 000	30 800
"	"	87 979	"	32 000	80 000	31 600
"	"	76 795	"	30 000	50 000	29 900
"	"	110 818	"	41 600	100 000	41 400
"	"	107 532	"	39 500	100 000	40 200
"	"	92 400	"	31 500	80 000	31 500
"	"	88 001	"	31 200	80 000	31 100
"	"	3 009	I. S.	40 300	100 000	40 300
"	"	89 391	I. C.	30 700	80 000	30 500
"	"	94 566	"	30 900	80 000	30 700
"	"	104 167	"	40 800	100 000	40 700
"	"	91 513	"	30 200	80 000	30 200
"	"	91 465	"	30 400	80 000	30 400
"	"	86 098	"	34 300	80 000	31 600
"	"	85 444	"	31 000	80 000	30 900
"	"	87 389	"	31 400	80 000	31 400
"	"	91 106	"	31 400	80 000	31 300
"	"	111 131	"	40 800	100 000	30 700
"	"	90 929	"	31 700	80 000	31 600
"	"	100 071	"	32 900	90 000	32 900
"	"	89 481	"	31 800	80 000	31 400
"	"	104 746	"	40 400	100 000	40 400
"	"	87 877	"	31 000	80 000	30 600
"	"	92 494	"	26 800	80 000	30 100
"	"	101 177	"	37 700	100 000	37 800
"	"	86 841	"	31 000	80 000	31 200
"	"	85 409	"	31 800	80 000	31 600
"	"	89 100	"	32 600	80 000	31 000
"	"	83 948	"	27 600	60 000	27 900
"	"	94 065	"	30 900	80 000	30 800
"	"	82 328	"	28 400	60 000	27 900
"	"	87 302	"	30 600	80 000	38 800
"	"	102 002	"	38 000	80 000	37 800
"	"	88 051	"	31 300	80 000	31 600
"	"	91 268	"	30 500	80 000	30 500
Caboose	"	98 413	"			34 800

APPENDIX 3

APPENDIX 3

THE TRACK

All tests, except No. S-1030A, were made over the 91 miles of Illinois Central main line track lying between Gilman (mile 81.12) and Mattoon (mile 172.38), Illinois.

Roadbed.—This track, formerly a part of one of the oldest single track lines in the State, was converted about ten years ago into a double track road; and the roadbed is now well settled and in good condition. In construction the roadbed has been made to conform as closely as practicable to the standard Illinois Central section for class A double track. This section has a 34-ft. crown with a slope of 1½ to 1 for embankments, and a 46½-ft. base with slopes of 1 to 1 or 1½ to 1 for cuts. The drainage of the track is, in general, excellent.

Ballast and Ties.—Except on a few short stretches through station grounds where screenings are used for ballast, both tracks are ballasted with broken limestone throughout this distance. There is not less than 12 in. of ballast beneath the ties, and the ballast shoulder extends 12 in. beyond the ties whence it runs off to the sub grade on a slope of 1¾ to 1. The cross ties are of either untreated white oak or treated red oak, and are 6 in. by 8 in. by 8 ft. long. They are spaced about 20 in. from center to center.

Rail.—The south-bound or west track between mile 161+3500 ft. and mile 171 is laid with rail weighing 75 lb. per yard. The remainder of the west track and all of the east track are laid with rail weighing 85 lb. per yard. The 75-lb. rail is of the standard American Society of Civil Engineers' section, rolled by the Illinois Steel Company, and is further designated as Illinois Steel Company's section No. 7506. All 85-lb. rail is of standard A. S. C. E. section, and Illinois Steel Company's section No. 8504.

Rail Joints and Fastenings.—All rails are laid with square joints, supported on three ties. The 75-lb. rails are joined with Illinois Central Standard 40-in. angle-bar splices, weighing 76 lb. per pair; and the 85-lb. rails are joined with similar splices weighing 80-lb. per pair. In each joint six track bolts are used, which are ¾ by 4⅛ in. for the 75-lb. rails, and ⅞ by 4½ in. for the 85-lb. rails. Four $\frac{9}{16}$ by 5½ in. track spikes are used in each cross tie. No tie plates or rail braces are used, except through switches.

Maintenance.—During eight months of the year there is employed in maintaining this portion of the road a force of men averaging one man per mile of track; during the remaining four months this force is reduced to one man for each two miles.

APPENDIX 4

APPENDIX 4

METHODS EMPLOYED IN CALCULATING THE RESULTS

This appendix presents a detailed explanation of the processes used throughout this investigation in deriving the results of the tests. Two methods of calculation have been employed. By one method resistance was determined at a point on the road; by the other, the average resistance was determined for the period during which the test car passed over a certain track section. The former is termed Method 1, the latter, Method 2. A general statement and comparison of the two methods and an explanation of the general limitations imposed upon the selection of points and sections have been given in Part I. Whatever is said under "Methods Employed in Calculating the Results" in Part I is to be considered as supplementary to the contents of this Appendix.

THE ELEMENTS OF GROSS RESISTANCE

The various elements which make up gross train resistance are:

1. Net resistance on straight, level track, at uniform speed, in still air.
2. Resistance due to wind, (as distinguished from still air resistance).
3. Resistance due to grade.
4. Resistance due to acceleration.
5. Resistance due to track curvature.

Item 1 is always in operation to retard a moving train. One or more (or none) of the others may also be acting with item 1 to form gross resistance.

The dynamometer car records directly the gross resistance or drawbar pull as here defined. The purpose of the calculations has been to determine net resistance (item 1); or more strictly speaking, the purpose, by force of circumstances, has been to determine the sum of net resistance (item 1), and wind resistance (item 2), since it has been impossible to differentiate the latter from the other elements. Curve resistance has been entirely eliminated from consideration by selecting for calculation only those points and sections where the train was on tangent track. Grade resistance and acceleration resistance may always be determined by calculation; and in order to find the net resistance, it is necessary only to subtract these two items (3 and 4) from the gross resistance recorded on the test car chart.

Since the process employed implies the ability to calculate the grade and acceleration resistances, their determination will be explained before proceeding with the explanation of the two methods by which net resistance was derived.

The following general notation is used throughout. Other special notation needed in the development of the analysis is given as the necessity arises.

NOTATION:

P = Total gross resistance = drawbar pull.—pounds.

R = Net resistance on tangent, level track, at uniform speed.—pounds per ton.

R_g = Resistance due to grade.—pounds per ton.

R_a = Resistance due to acceleration.—pounds per ton.

W = Total train weight.—tons.

V, V_1, etc. = Train speed.—miles per hour.

G = Grade.—feet per mile.

A = Acceleration of the train speed.—miles per hour per second.

a = Acceleration of the train speed.—feet per second per second.

E_1 and E_2 = Elevations of the center of mass of the train.—feet.

S = Length of track section used in Method 2.—feet.

N = Number of cars in the train.

GRADE RESISTANCE

If the train be on a uniform grade of G feet per mile, the grade resistance in pounds per ton is at the moment:

$$R_g = 0.379 \times G \qquad (15).$$

If it be desired to find the average grade resistance during the period in which the test car passes a certain section of track, we must determine the elevations of the center of mass of the train at the moments the car enters and leaves the section. If we call these elevations E_1 and E_2 respectively, and the length of the section S (in feet), then the average grade in feet per mile is:

$$G = (E_2 - E_1) \times \frac{5280}{S}$$

and

$$R_g = 0.379 \times (E_2 - E_1) \times \frac{5280}{S} = \frac{2001\,(E_2 - E_1)}{S} \ldots\ldots (16).$$

G and $(E_2 - E_1)$ in these equations may be found directly from the profile; and S may be calculated from the profile or from the dynamometer chart. To give correct results, the entire train must be on uniform grade at the moments for which G, E_1 and E_2 are determined.

ACCELERATION RESISTANCE

The total force needed to produce acceleration is made up of two parts. The first is the force needed to produce acceleration in the motion of translation of the train as a whole; and the second is the force needed to produce acceleration in the rotation of the wheels and axles. This total force is the total acceleration resistance R_a.

Let

R_a = Acceleration resistance due to both translation and rotation.—pounds per ton.

F = Total drawbar pull needed to produce the acceleration.—pounds.

T = Drawbar pull needed to produce acceleration in the translation of the whole train.—pounds.

f = Drawbar pull needed to produce acceleration in the rotation of all wheels and axles. - pounds.

Then

$$R_a = \frac{F}{W}$$

and

$$F = T + f$$

therefore

$$R_a = \frac{T + f}{W} \ldots\ldots\ldots\ldots\ldots\ldots (17).$$

T and f in this equation are found as follows:

$$T = \text{mass} \times \text{acceleration} = \frac{W \times 2000}{32.2} \times a$$

but

$$a = A \times \frac{5280}{60 \times 60} = 1.466\,A$$

hence

$$T = \frac{W \times 2000 \times 1.466\,A}{32.2} = 91.05\,A\,W \ldots\ldots (18).$$

To find f:

Let

p = Drawbar pull required to produce the acceleration in the rotation of one pair of wheels and their axle.—pounds. This is to be considered as a force applied at the wheel rim.

p_1 = Force which, applied at the end of the "radius of gyration", would produce the acceleration in rotation produced by p.

r = Wheel radius.—any unit.

k = Radius of gyration of one pair of wheels and axle.—same unit as r.

w = Weight of one pair of wheels and their axle. — pounds.

a = Acceleration in the linear velocity of a point on the wheel rim.—feet per second per second. This equals the acceleration of the train.

b = Acceleration in the linear velocity of a point at the end of the radius of gyration.—feet per second per second.

w is taken as equal to 1950 lb[1], which is the approximate mean between the weight of a $4\frac{1}{4}$ by 8 axle and its wheels and the weight of a 5 x 9 axle and its wheels. $\frac{k}{r}$ is found to be about 0.64 for various axles and wheels[1].

Since cars have 4 axles, we have:

$$f = 4\,N \times p$$

$$p = \frac{k}{r} \times p_1$$

$$p_1 = \frac{w}{32.2} \times b = \frac{1950}{32.2} \times b = 60.56\,b$$

$$b = a\,\frac{k}{r} = 1.466\,A \times \frac{k}{r}$$

$$p_1 = 60.56 \times 1.466\,A \times \frac{k}{r} = 88.82\,A \times \frac{k}{r}$$

$$p = 88.82\,A \times \frac{k^2}{r^2} = 88.82 \times (0.64)^2 \times A = 36.38\,A,$$

and

$$f = 4 \times N \times 36.38\,A = 145.5\,A\,N \qquad (19)$$

---

[1] The maximum error in Ra which may result from possible variations in w and $\frac{k}{r}$ under current standards of car design is 1.1 per cent. Ra in the calculations seldom exceeds R, and the maximum probable error in R due to such variations is therefore about one per cent. It would occur with a train of *empty* gondolas equipped with 5½ x 10 journals and wheels weighing 725 lb. each.

From equations 17, 18, and 19

$$R_a = \frac{T}{W} + \frac{t}{W}$$

Hence

$$R_a = \quad (91.05 + 145.5 \frac{N}{W}) \times A \ldots\ldots\ldots\ldots\ldots (20).$$

Formula 20 may be applied to find the momentary acceleration resistance at a point on the road, or to determine its average value while the train passes a certain section. In the former case A denotes the momentary acceleration, and in the latter case A denotes the average acceleration over the section. N and W are derived from the train data. In either case A may be found as explained below.

The determination of acceleration.—In determining the net resistance by Method 1—at a point on the road—the momentary value of A in formula 20 has been determined as follows. In this discussion it should be remembered that all curves on the dynamometer chart are drawn on a distance base, i. e., to some scale their abscissas represent distances, in feet.

On the speed curve in Fig. 17, let B represent the point on the road which is under consideration. At B draw the tangent $O\ D$ to this curve, and select on this tangent the points C and D *equidistant* from B. This tangent may be considered as a speed curve which at B represents the same acceleration as the actual speed curve. By direct measurement the ordinates of the tangent at C and D are determined as v_1 and v_2, respectively. Similarly the distance S may be determined. The speed at B is called v. The acceleration A at the point B is then determined thus:

Let

v, v_1, v_2 = Speed.—feet per second.

V_1, V_2 = Speed.—miles per hour.

t = Time.—seconds.

l = Distance.—feet.

a = Acceleration.— feet per second per second.

Then

$$a = \frac{d\,v}{d\,t}$$

and

$$d\,t = \frac{d\,l}{v}$$

hence

$$a = \frac{vdv}{dl}$$

The equation of the tangent referred to the axes Ov and Ol is:

$$v = ml$$

$$m = \frac{v_2 - v_1}{S}$$

$$v = \frac{v_2 - v_1}{S} \times l$$

whence

$$d\,v = \frac{v_2 - v_1}{S}\,d\,l$$

and

$$\frac{d\,v}{dl} = \frac{v_2 - v_1}{S}$$

also, since v is the mean between v_1 and v_2,

$$v = \frac{v_2 + v_1}{2}$$

therefore

$$a = \frac{vdv}{d\,l} = \frac{v_2 + v_1}{2} \times \frac{v_2 - v_1}{S} = \frac{v_2^2 - v_1^2}{2\,S}$$

but

$$a = 1.466\ A$$

and

$$v = 1.466\ V,$$

hence

$$A = \frac{(1.466)^2 \times (V_2^2 - V_1^2)}{1.466 \times 2\ S} = 0.733 \frac{V_2^2 - V_1^2}{S} \quad \ldots\ldots\ldots\ldots(21).$$

Formula 21 is used to determine the momentary acceleration at a point B on the speed curve. V_1 and V_2 are ordinates at the two points, C and D, located on the tangent drawn at B and equidistant from B. To draw this tangent with sufficient accuracy, the speed curve must be nearly a straight line for a small distance on either side of B.

In determining the net resistance by Method 2—while the test car passes a certain track section—the average value of A in formula 20 has been determined as follows. The conditions are represented in Fig. 18.

Let a = the *uniform* acceleration which, acting during the passage of the car through the section, would have caused a speed change the same as that actually produced.—feet per second per second.

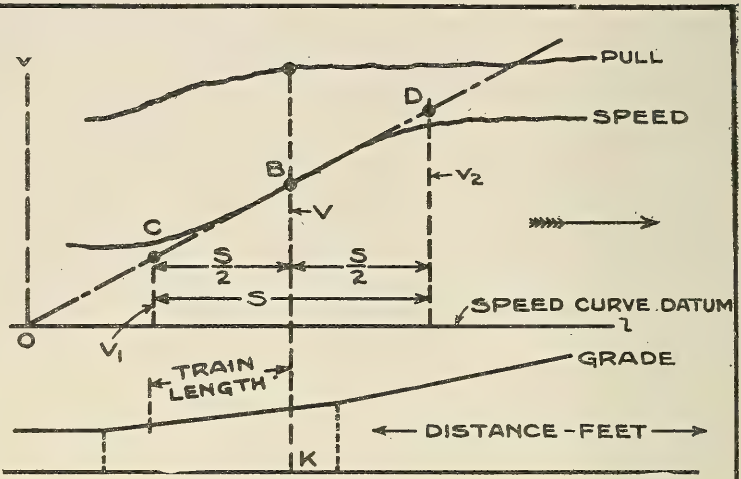

FIGURE 17

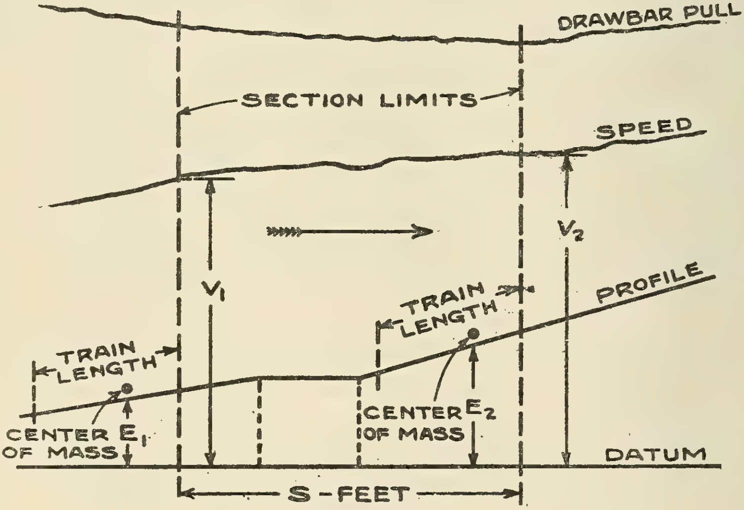

FIGURE 18

FIG. 17 DIAGRAM USED IN THE EXPLANATION OF METHOD I
FIG. 18. DIAGRAM USED IN THE EXPLANATION OF METHOD II

A = The same, expressed in miles per hour per second.
v_1 and v_2 = Speeds at entrance and exit.—feet per second.
V_1 and V_2 = Speeds at entrance and exit.—miles per hour.
S = The length of the section.—feet.
t = The time elapsed in transit over the section.—seconds.

Then

$$v_2 = v_1 + a\,t$$

and

$$S = v_1 t + \frac{a\,t^2}{2}$$

whence, by the elimination of t,

$$a = \frac{v_2^2 - v_1^2}{2\,S}$$

and, since

$$a = 1.466\,A$$

and

$$v = 1.466\,V,$$

$$A = 0.733\,\frac{V_2^2 - V_1^2}{S} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (22)$$

This equation is identical in form with equation 21. It is used to determine the average acceleration over a given track section. In it A is to be understood as that hypothetical uniform acceleration which, acting during transit over the section, would have caused the absorption of the same energy as was actually expended to produce acceleration under the prevailing speed changes. V_1 is the speed at the moment the head of the train enters the section. V_2 is the speed at the moment the head of the train leaves the section. S is the length of the section.

Formula 22 is correct for all cases, regardless of the shape or variations of the speed curve. However, for reasons which are entirely unrelated to the accuracy of the acceleration determination and which have been explained in Part I, the sections were so chosen that V_1 and V_2 varied but slightly, and that the speed curve between the section limits presented no great speed variations.

THE DETERMINATION OF NET RESISTANCE

Net resistance on straight, level track, at uniform speed is termed R, and is expressed in pounds per ton. In both methods of calculation its value was derived from the equation:

$$R = \frac{P}{W} - R_g - R_a \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (23).$$

In which P is determined from the test car chart, W from train data, and R_g and R_a as previously explained.

Method No. 1.—To determine R at a point on the track, equations 23, 15, and 20 may be used; these when combined give us:

$$R = \frac{P}{W} - 0.379G - (91.05 + 145.5\frac{N}{W}) \times A \ldots\ldots\ldots\ldots (24).$$

If the train is on a down grade the sign of the second term should be changed to plus. The value of A should be found by means of equation 21, and, as there explained, by drawing a tangent to the speed curve. The other quantities in the equation,—W, N, P, S, and G, may be found directly from the train data, or the dynamometer chart, or the profile. Fig. 17 represents the conditions which prevailed at points chosen for the calculations by this method. In Fig. 17 the line KB represents the point on the road which is under consideration. All values of momentary resistance included in this report have been found by means of formula 24.

In the selection of points for the application of Method 1, the following precautions must be and have been observed:

1. The entire train must be on tangent track and on a uniform grade.
2. The speed curve must be nearly straight for a certain distance either side of the point chosen, in order to permit the tangent to be accurately drawn.
3. The acceleration should preferably be low. The maximum acceleration at any point chosen for the calculation of values included in this report was 0.106 miles per hour per second.

Method No. 2. To determine the mean value of R over a certain track section, equations 23, 16, and 20 may be used; these when combined give:

$$R = \frac{P}{W} - \frac{2001 \times (E_2 - E_1)}{S} - (91.05 + 145.5\frac{N}{W}) \times A \ldots\ldots (25).$$

In this case the value of A should be found by means of equation 22. The quantities to be determined in order to use formula 25 are W, N, P, S, V_1, V_2 and $(E_2 - E_1)$. W and N are derived from the train data. P is the mean drawbar pull over the section, and is found by determining by the use of a planimeter the mean height of the pull curve between the section limits. S is the section length and may be found directly from the dynamometer chart. V_1 is the speed as the train enters the section. V_2 is the speed as the train leaves the section. V_1 and V_2 are determined directly from the dynamometer chart. E_1 is the elevation of the center of mass of the train at the moment its head end enters the section. E_2 is the corresponding elevation at the moment the head end of the train leaves the section. The quantity $(E_2 - E_1)$ is found from the profile. R in this case corresponds to the mean speed over the section. This mean speed is determined by means of the records of time and distance. Fig. 18 represents the conditions which prevailed at sections chosen for the calculations by this method. In Fig. 15, Appendix 1, is represented the section from which the results for item 12 of test S-1057 were derived. All values of mean resistance included in this report have been found by formula 25.

In the selection of points for the application of Method 2, the following precautions must be and have been observed:

1. The track must be straight over the section and also for a distance (equal to the train length) before the entrance to the section.
2. The entire train must be on a uniform grade at the moment its head end enters the section, and again at the moment it leaves the section. These grades need not, however, be alike.
3. For reasons which have been explained in Part I, the speed curve between the section limits should not present great speed variations nor should the difference between V_1 and V_2 be greater than ten or twelve miles per hour.

APPENDIX 5

APPENDIX 5

THE RESULTS OF THE INDIVIDUAL TESTS

Appendix 5 exhibits for each test a table showing the main results of the calculations. Where both methods of calculation have been employed, the tables show two groups of items. The one group displays the results obtained by Method 1, and the other shows those obtained by Method 2. The notation following the column headings is the same as that used in Appendix 4. The final values of net resistance on tangent, level track, at uniform speed are given in column 13, and the corresponding values of speed are given in column 12.

Following the table of results for each test is a figure which shows the relation between speed and resistance for the same test. The coordinates of the points plotted in these diagrams are the values of speed and resistance given in columns 12 and 13 of the corresponding table. The points represented in the diagrams by circles are plotted from values of momentary speed and momentary resistance obtained by Method 1. The points represented by circular black spots are plotted from values of average speed and average resistance obtained by Method 2. The numbers shown at the points are the corresponding item numbers given in column 2 in the table.

The curves represent for each test the mean relation between resistance and speed. In order to draw these curves, the plotted points were assumed to be arranged in a number of groups for each of which the "center of gravity" was determined and plotted on the diagram. The curve was then drawn by confining attention to the few points thus determined. The groups of points were arbitrarily selected so that the resulting "centers of gravity" were almost equidistantly distributed throughout the speed range.

TABLE 36 TEST NO. S-1013

From Champaign to Gilman, April 27, 1908. Weather: Intermittent rain. Temperature: 42° F. at start, 44° F. at end of test. Total weight behind measuring drawbar = 2549 tons, including the test car. Train length = 2784 ft. Center of mass 1425 ft. back of measuring drawbar. 67 cars: 10 empty, 57 loaded. Kind of cars: 53 box, 9 gondola, 3 tank, 1 test, 1 caboose. Average weight per car = 38.04 tons.

1	2	3	4	5	6	7	8	9	10	11	12	13
Method of Calculation	Item No.	Location on Road	Length of Section feet	Total Drawbar Pull pounds	Acceleration miles per hour per second	Speeds		Grade + Up — Down feet per mile	Wind		Speed m. p. h.	Net Train Resistance pounds per ton
		Milepost No.				At Entrance to Section m. p. h.	At Exit from Section m. p. h.		Approximate Direction	Approximate Velocity m. p. h.		
				P	A	V_1	V_2	G			V	R
Point Columns 5, 6, and 9 to 13 show Momentary Values	2	116.67		16400	0			+1.48	+50°L	18	18.20	5.86
	3	112.23		13750	0			—2.78	90°L	19	24.30	6.45
	4	110.46		29600	0			+16.50	90°L	19	11.50	5.34
	5	108.80		11900	0			—4.82	+40°L	25	24.60	6.50
	7	105.86		9850	0			—10.00	+50°L	22	32.70	7.65
	8	100.51		23000	0			+8.52	+90°L	17	12.70	5.79
	9	99.29		12750	0			—5.74	+35°L	21	27.50	7.18
	10	91.00		12500	0			—2.59	+55°L	15	26.30	5.89
	11	90.08		12550	+0.0280			—9.32	+55°L	27	27.50	5.81
	12	87.00		13100	0			—2.23	+45°L	17	24.10	5.99
	13	86.15		15300	0			0.00	90°L	17	20.70	6.00
	14	84.46		16400	—0.0200			+6.20	90°L	14	18.40	6.00
	15	83.24		12250	0			—5.00	90°L	21	25.10	6.71
	16	81.86		13000	0			—1.67	90°L	15	16.00	5.73
Section Columns 5, 6, and 9 to 13 show Average Values	4	116.25—117.00	3960	16400		18.20	18.20	+2.00	+50°L	18	18.20	5.68
	5	110.46—111.00	2870	30000		11.60	11.60	+19.32	+90°L	19	11.60	4.45
	6	100.82—101.55	3880	23700		12.60	12.60	+10.60	+90°L	17	12.60	5.29

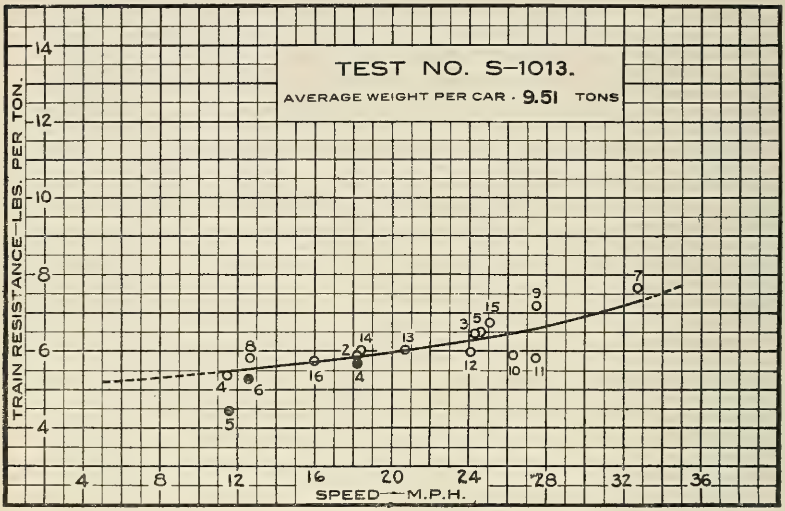

Fig. 19 to 50 Curves Showing the Relation Between Resistance and Speed for Each of the 32 Tests

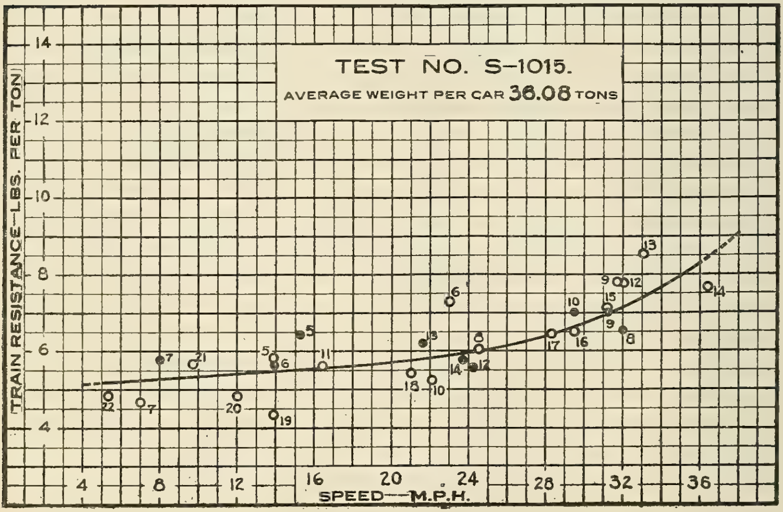

Fig. 20

TABLE 37 TEST NO. S–1015*

From Champaign to Gilman, April 29, 1908. Weather: Fair. Temperature: 40° F. at start, 48° F. at end of test. Total weight behind measuring drawbar = 2489 tons, excluding the test car. Train length = 2520 ft. Center of mass 1200 ft. back of measuring drawbar. 69 cars: 8 empty, 61 loaded. Kind of cars: 46 box, 4 gondola, 11 flat, 7 tank, 1 caboose. Average weight per car = 36.08 tons.

1	2	3	4	5	6	7	8	9	10	11	12	13
Method	Item	Mile Post	Section Length	Pull P	Accel. A	Speed V_1	Speed V_2	Grade G	Direction	Velocity	Speed V	Resistance R
Point Columns 5, 6, and 9 to 13 Show Momentary Values	5	114.35		21800	0			+ 7.96	+80°L	6	13.90	5.84
	6	112.27		14800	0			− 3.56	+50°L	10	23.00	7.30
	7	110.64		31000	0			+20.50	+65°L	7	7.00	4.68
	8	108 67		13900	−0.0220			+ 4.39	+60°L	9	24.50	6.02
	9	105.95		10500	+0.0220			−15.04	+40°L	15	31.77	7.80
	10	101.76		11600	0			− 1.47	+30°L	12	22.10	5.23
	11	100.49		18500	0			+ 4.82	+55°L	6	16.40	5.61
	12	96.94		3750	0			−16.55	+35°L	15	32.10	7·79
	13	96.00		5500	+0.0621			−27.00	+45°L	15	33.10	8·51
	14	95.48		3500	+0.0300			−24.00	+55°L	11	36.40	7·65
	15	94.00		5250	0			−13.20	+30°L	16	31.25	7·11
	16	92.00		5500	0			−11.30	+60°L	7	29.50	6·50
	17	90.00		7750	0			− 8.80	+80°L	12	28.25	6·44
	18	86.00		12500	0			− 1.05	−80°L	10	21.00	5·42
	19	103.44		25800	−0.0587			+30.60	+35°L	10	13.90	4·35
	20	103.35		28000	−0.0587			+31.60	+25°L	8	12.00	4·84
	21	103.25		31600	−0.0587			+33.00	+25°L	6	9.70	5·69
	22	103.02		36750	−0.0140			+29.70	+65°L	2	5.28	4·85
Section Columns5, 6, and 9 to13 show Average Values	6	114.81—114.18	3310	22200		13.90	13.90	+ 8.62	+80°L	6	13.90	5.66
	7	111 22—110.58	3380	31500		9.00	7.00	+19.82	+65°L	7	8.00	5.80
	8	97.16— 96.19	5160	5250		31.40	31.70	−12.38	+55°L	11	32.00	6 51
	9	94.18— 93.54	3420	5250		31.20	31.20	−12.96	+30°L	16	31.20	7.03
	12	88.14— 87.12	5380	10000		24.20	24.20	− 4.12	+40°L	10	24.20	5.58
	13	86.31— 85.44	4650	12500		21.50	21.70	− 3.52	−80°L	10	21.60	6.21
	14	83.80— 82.79	5380	11200		22.80	24.70	− 6.48	+80°L	12	23.70	5.79

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* For complete table heading see Table 36, p. 99.

TABLE 38 TEST NO. S-1016*

From Gilman to Champaign, April 30, 1908. Weather: Fair. Temperature: 44° F. at start, 48° F. at end of test. Total weight behind measuring drawbar = 1161 tons, including the test car. Train length = 3030 ft. Center of mass 1515 ft. back of measuring drawbar. 72 cars: 72 empty, 0 loaded. Kind of cars: 70 gondolas, 1 test, 1 caboose. Average weight per car = 16 12 tons.

1	2	3	4	5	6	7	8	9	10	11	12	13
Method	Item	Mile Post	Section Length	Pull P	Accel. A	Speed V_1	Speed V_2	Grade G	Direction	Velocity	Speed A	Resistance R
Point Columns 5, 6, and 9 to 13 show Momentary Values	9	94.57		14400	0			+12.21	+55°R	14	11.20	7.77
	10	95.55		10450	0			+ 5.06	+60°R	10	16.30	7.08
	11	96.61		20250	0			+25.80	+55°R	10	9.50	7.66
	12	98.67		21500	0			+28.80	+55°R	6	8.30	7.60
	15	105.66		6250	—0.0118			— 8.20	+30°R	12	24.10	9.74
	16	106.27		9250	—0.0300			— 4.44	+35°R	11	22.90	9.28
	17	106.91		13600	—0.0117			+13.25	+35°R	7	17.10	7.85
	18	107.39		14750	—0.0117			+17.40	+30°R	10	16.60	7.27
	19	107.75		14700	—0.0117			+16.20	+25°R	9	15.00	7.67
	21	115.89		7500	0			— 7.32	+20°R	9	23.60	9.23
	22	117.65		8000	0			— 1.57	+20°R	9	21.30	7.48
	23	109.22		9900	0			— 1.92	+30°R	11	20.10	9.26
	24	99.70		8750	0			— 4.87	+20°R	15	18.90	9.38
Section Columns 5, 6, and 9 to 13 show Average Values	5	98.23— 98.85	3280	21000		9.25	7.40	+29.90	+55°R	6	8.75	7.43
	6	104.37—104.88	2675	6000		25.00	25.00	—16.78	+40°R	10	25.00	11.52
	7	105.17—105.66	2596	6200		25.65	24.53	—11.30	+40°R	11	25.30	11.15
	8	105.66—106.27	3208	8400		24.28	22.90	— 3.62	+30°R	12	24.00	10.10
	9	106.91—107.37	2430	14000		18.20	16.60	+14.13	+35°R	7	17.40	7.56
	10	107.37—107.75	2030	14300		16.60	14.90	+16.65	+30°R	10	15.70	7.96
	11	115.65—116.15	2640	7400		23.30	23.30	— 6.40	+20°R	9	23.40	8.79
	12	116.68—117.65	5120	7750		22.50	21.40	— 2.68	+20°R	9	21.95	7.77
	13	118.17—120.37	11570	10250		22.00	23.30	— 0.14	+15°R	11	22.65	8.51
	14	120.33—121.64	6950	10000		23.30	24.20	— 2.58	+35°R	8	23 75	9.13
	15	123.20—125.07	9880	10200		22.30	22.30	— 0.27	+35°R	9	22.30	8.90
	16	111.45—111.79	1752	6600		24.16	26.15	—22.90			25.15	10.18
	17	111.79—112.28	2604	6500		26.15	29.10	—29.65			27.65	12.26
	18	112.28—112.62	600	3500		29.17	29.42	—28.20			29.20	11.87

* For complete table heading see Table 36. p. 99.

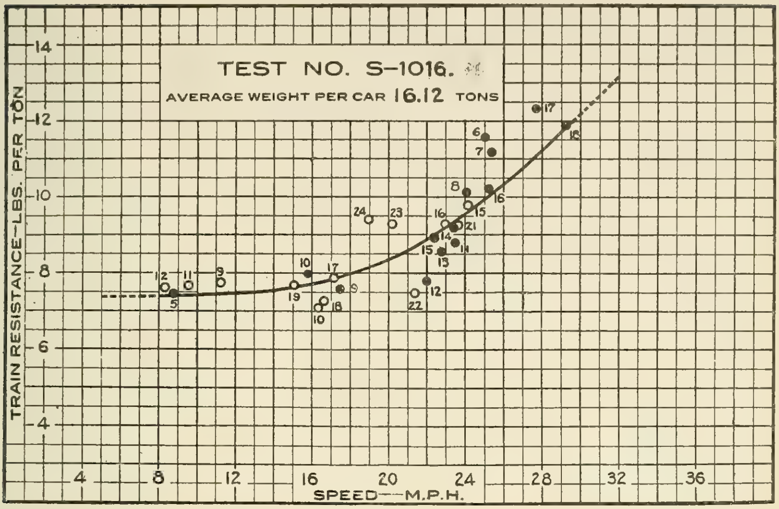
TEST NO. S-1016.
AVERAGE WEIGHT PER CAR 16.12 TONS
TRAIN RESISTANCE—LBS. PER TON
14
12
10
8
6
4
SPEED—M.P.H.
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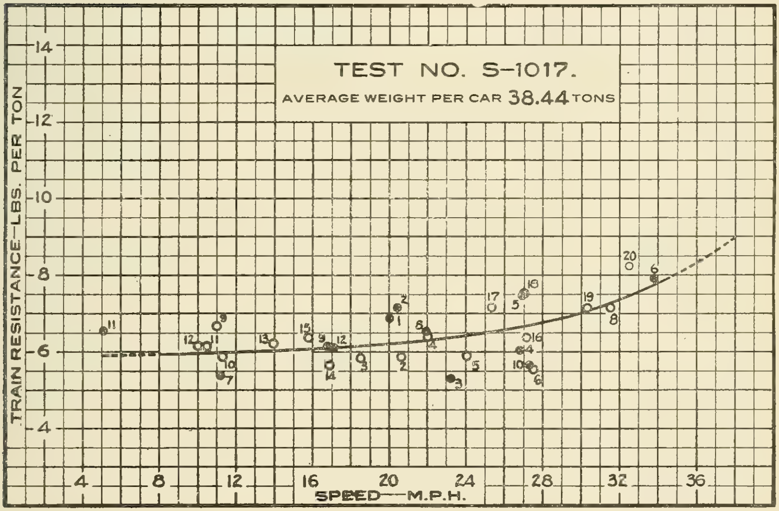
FIG. 21


TEST NO. S-1017.
AVERAGE WEIGHT PER CAR 38.44 TONS
TRAIN RESISTANCE—LBS. PER TON
14
12
10
8
6
4
SPEED—M.P.H.
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24
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FIG. 22

TABLE 39 Test No. S-1017*

From Champaign to Gilman, May 1, 1908. Weather: Intermittent rain. Temperature: 48° F. at start, 54° F. at end of test. Total weight behind measuring drawbar = 2532 tons, excluding the test car. Train length = 2670 ft. Center of mass 1200 ft. back of measuring drawbar. 66 cars: 13 empty, 53 loaded. Kind of cars: 62 box, 3 gondola, 1 caboose. Average weight per car = 38.44 tons.

1	2	3	4	5	6	7	8	9	10	11	12	13
Method	Item	Mile Post	Section Length	Pull P	Accel. A	Speed V_1	Speed V_2	Grade G	Direction	Velocity	Speed V	Resistance R
Point Columns 5, 6, and 9 to 13 shown Momentary Values	2	85.23		11250	0			− 3.71	+75°L	18	20.60	5.86
	3	86.16		14700	0			− 0.00	+70°L	16	18.50	5.81
	4	88.12		10000	0			− 6.45	+65°L	19	22.00	6.40
	5	90.00		6500	0			− 8.47	+50°L	37	24.00	5.88
	6	91.25		5750	0			− 8.54	+65°L	20	27.50	5.51
	8	95.82		5850	+0.0465			−24.35	+85°L	13	31.50	7.14
	9	100.71		25300	0			+ 8.90	+60°L	22	11.00	6.62
	10	101.48		21900	−0.0101			+10.20	+90°L	14	11.35	5.84
	11	103.69		29000	−0.0500			+27.80	+70°L	14	10.50	6.14
	12	103.60		30100	−0.0545			+28.90	+75°L	13	10.00	6.11
	13	103.89		25500	−0.0500			+22.60	+70°L	16	14.00	6.20
	14	104.53		19900	−0.0388			+15.50	−85°L	16	16.90	5.66
	15	104.41		21850	−0.0388			+15.64	−85°L	12	15.80	6.38
	16	105.71		12250	0			− 4.05	+85°L	10	27.20	6.37
	17	106.30		14250	+0.0325			−12.10	+65°L	9	25.30	7.14
	18	106.00		12750	+0.0325			−14.72	+60°L	12	27.00	7.53
	19	96.00		5350	+0.0550			−27.05	+80°L	11	30.30	7.14
	20	95.65		3500	+0.0425			−28.70	+80°L	17	32.50	8.25
Section Columns 5, 6, and 9 to 13 show Average Values	1	82.41— 82.00	2152	17300		20.10	19.40	+ 2.20	+45°L	9	20.00	6.89
	2	87.56— 86.80	4348	16100		22.10	21.32	− 0.66	+65°L	12	20.40	7.15
	3	89.10— 88.59	2372	9000		23.40	22.70	− 1.90	+50°L	21	23.20	5.22
	4	92.00— 91.25	3970	6500		26.30	27.20	−11.43	+65°L	20	26.80	6.02
	5	94.13— 93.63	2624	6600		27.15	27.33	−13.55	+80°L	21	26.90	7.49
	6	95.30— 95.10	988	3400		33.55	33.95	−20.80	+60°L	14	33.75	7.90
	7	101.50—101.00	2620	24000		11.60	10.70	+12.23	+90°L	14	11.20	5.38
	8	105.74—105.34	2088	19150		21.90	21.90	+ 2.79	+70°L	16	21.90	6.51
	9	104.40—104.10	1580	24500		16.30	16.30	+13.35	−85°L	15	16.80	6.13
	10	105.72—105.42	1640	12500		27.30	26.50	+ 2.90	−85°L	10	27.30	5.63
	11	111.16—110.86	1600	35800		5.10	5.10	+19.80	−80°L	13	5.10	6.60
	12	116.00—115.50	2240	17200		17.10	17.00	+ 2.24	−85°L	13	17.10	6.08

* For complete table heading see Table 36, p. 99.

TABLE 40 Test No. S-1018*

From Gilman to Champaign, May 2, 1908. Weather: Fair. Temperature: 40° F. at start, 45° F. at end of test. Total weight behind measuring drawbar = 1353 tons, including the test car. Train length = 2130 ft. Center of mass 1000 ft. back of measuring drawbar. 49 cars: 34 empty, 15 loaded. Kind of cars: 28 box, 3 gondola, 8 flat, 8 tank, 1 test, 1 caboose, and 2 I. C. locomotives, No. 423 and No. 732 with tenders. Average weight per car = 25.40 tons.

1	2	3	4	5	6	7	8	9	10	11	12	13
Method	Item	Mile Post	Section Length	Pull P	Accel. A	Speed V_1	Speed V_2	Grade G	Direction	Velocity	Speed V	Resistance R
Point Columns 5, 6, and 9 to 13 show Momentary Values	5	93.94		13300	0			+ 8.92	+85°R	15	16.00	6.47
	6	94.59		14600	0			+10.90	+70°R	12	14.70	6.67
	7	96.34		20600	−0.0018			+26.50	+55°R	7	10.60	5.32
	8	97.29		14750	−0.0042			+ 9.30	+45°R	13	17.95	7.78
	9	98.68		22000	−0.0048			+28.80	+60°R	8	9.45	5.82
	10	100.15		18500	−0.0025			+22.00	+85°R	14	13.10	5.57
	11	102.00		9470	+0.0159			− 8.90	+75°R	13	24.80	8.83
	12	104.43		4750	−0.0263			−20 10	+10°R	23	30.20	8.59
	13	105.34		5000	−0.0046			−10.15	+65°R	14	29.30	8.00
	14	106.25		7000	−0.0419			+ 7.44	+45°R	12	26.30	6.40
	15	106.40		8300	−0.0645			+13.90	+50°R	11	25.70	7.12
	16	106.53		8550	−0.0644			+15.40	+55°R	10	24.20	6.72
	17	106.64		9350	−0.0596			+15.60	+60°R	11	23.15	6.77
	18	106.71		10250	−0.0419			+14.37	+60°R	10	22.50	6.18
	19	106,90		10000	−0.0419			+12.15	+45°R	11	21.00	6.85
	20	107.07		11000	−0.0419			+14.38	+45°R	9	19.70	6.74
	21	107.47		12000	−0.0419			+17.10	+45°R	8	17.00	6.44
	22	108.23		16000	0			+16.10	+45°R	7	13.80	5.72
	23	109.17		8750	0			− 2.72	+45°R	10	21.50	7.50
	26	115.94		9200	0			− 5.70	+35°R	12	23.20	7.00
Section Columns 5, 6, and 9 to 13 show Average Values	3	92.00— 92.51	2675	12800		16.20	15.20	+11.20	+80°R	13	15.80	6.00
	4	96.22— 96.74	2770	21250		11.30	11.30	+25.50	+55°R	7	11.40	6.02
	5	104.43—105.34	4800	5100		29.70	29.20	−14.30	+65°R	14	29.50	9.62
	8	126.00—126.45	2400	9600		18.20	17.70	+ 3.08	+60°R	12	17.68	6.46
	11	98.55— 98.85	1588	22000		10.35	10.12	+25.70	+6°0R	8	9.40	6.72
	12	101.70—102.00	1584	10100		23.41	24.77	−11.00	+75°R	13	24.00	8.74
	13	108.08—108.41	1748	15000		14.20	14.00	+16.30	+45°R	7	14.20	5.21
	14	106.00—107.30	6840	9300		28.05	18.23	+12.50			22.80	6.82
	15	106.00—106.53	2750	7500		28.05	24.32	+ 7.88			26.60	7.59
	16	106.53—107.30	4096	10500		24.32	28.23	+15.10			20.90	6.52

* For complete table heading see Table 36, p. 99.

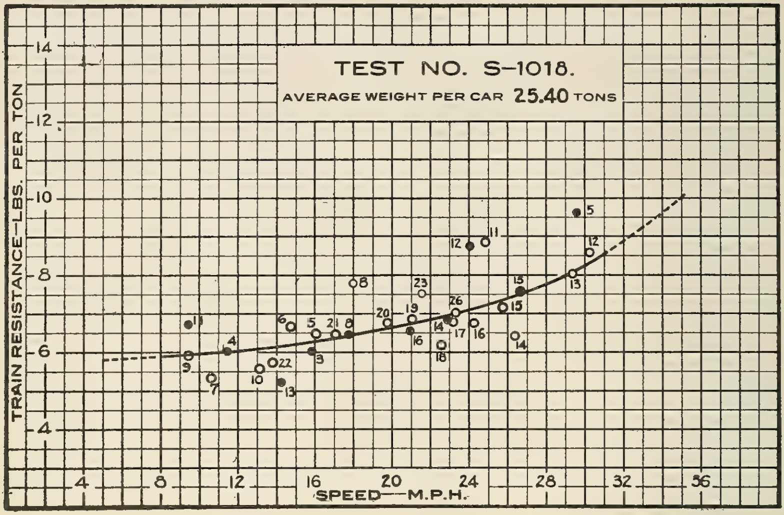
TEST NO. S–1018.
AVERAGE WEIGHT PER CAR 25.40 TONS
TRAIN RESISTANCE—LBS. PER TON
14
12
10
8
6
4
4
8
12
16
20
24
28
32
36
SPEED—M.P.H.

FIG. 23

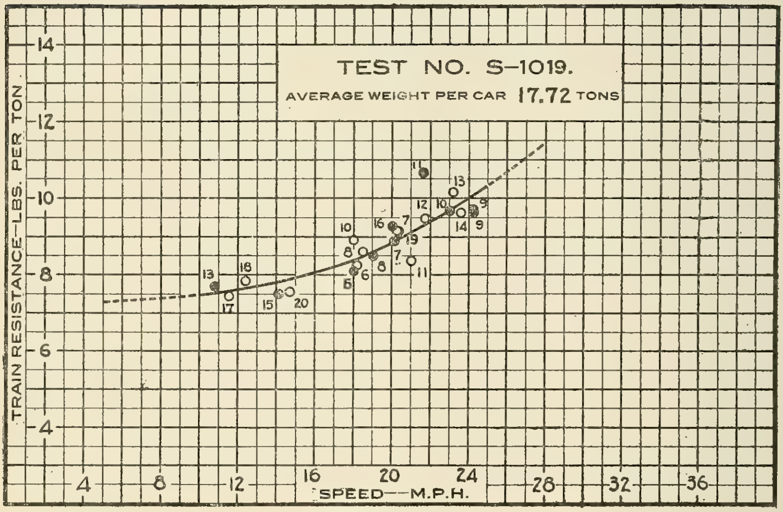
TEST NO. S–1019.
AVERAGE WEIGHT PER CAR 17.72 TONS
TRAIN RESISTANCE—LBS. PER TON
14
12
10
8
6
4
4
8
12
16
20
24
28
32
36
SPEED—M.P.H.

FIG. 24

TABLE 41 TEST No. S-1019*

From Champaign to Mattoon, May 9, 1908. Weather: Fair. Temperature: 44° F. at start, 62° F. at end of test. Total weight behind measuring drawbar = 1572 tons, excluding the test car. Train length = 3480 ft. Center of mass 1600 ft. back of measuring drawbar. 89 cars: 75 empty, 14 loaded. Kind of cars: 29 box, 52 gondola, 6 flat, 1 tank, 1 caboose. Average weight per car = 17.72 tons.

1	2	3	4	5	6	7	8	9	10	11	12	13
Method	Item	Mile Post	Section Length	Pull P	Accel. A	Speed V_1	Speed V_2	Grade G	Direction	Velocity	Speed V	Resistance R
Point Columns 5, 6, and 9 to 13 show Momentary Values	6	141.18		10700	0			— 3.75	+30° R	21	18.20	8.23
	7	143.80		9000	0			— 9.03	+25° R	27	20.25	9.14
	8	144.90		11000	0			— 4.16	+30° R	21	18.50	8.58
	9	147.30		7500	0			—12.70	+20° R	30	24.30	9.61
	10	149.80		11800	0			— 3.64	+30° R	21	18.00	8.89
	11	145.98		9000	+0.0289			—14.52	+20° R	31	21.00	8.36
	12	146.19		8700	+0.0289			—17.95	+20° R	31	21.75	9.46
	13	146.38		8050	+0.0240			—19.50	+35° R	21	23.20	10.14
	14	146.54		7400	+0.0289			—20.50	+20° R	31	23.60	9.62
	17	157.13		16000	0			+ 7.21	+25° R	18	11.56	7.44
	18	159.82		15400	0			+ 5.22	+25° R	18	12.45	7.82
	19	161.44		9800	0			— 7.66	+20° R	32	20.30	9.13
	20	165.93		13250	0			+ 2.30	+45° R	15	14.70	7.54
Section Columns 5, 6, and 9 to 13 show Average Values	6	141.18—141.56	2370	10900		17.90	17.90	— 3.03	+30° R	21	18.00	8.09
	7	143.80—144.27	2450	9200		20.20	20.00	— 7.33	+25° R	27	20.10	8.86
	8	144.89—145.44	2890	10200		18.50	19.50	— 7.80	+30° R	21	19.00	8.49
	9	146.98—144.47	2568	7000		24.25	24.25	—13.76	+20° R	30	24.25	9.67
	10	146.19—146.54	1856	8250		21.54	23.86	— 7.90	+20° R	31	23.00	9.67
	11	145.99—146.38	2064	8850		20.85	23.18	— 8.90	+20° R	31	21.65	10.66
	13	155.83—156.33	2640	18000		10.78	10.78	+ 9.90	+35° R	19	10.78	7.70
	15	165.66—166.16	2640	12950		14.00	14.00	+ 2.00	+30° R	21	14.10	7.48
	16	161.21—161.61	2112	10100		19.83	19.97	— 3.20	+20° R	32	20.00	9.26

*For complete table heading see Table 36, p. 99.

TABLE 42 TEST NO. S-1021*

From Rantoul to Paxton, May 13, 1908. Weather: Continuous Rain. Temperature: 66° F. at start, 70° F. at end of test. Total weight behind measuring drawbar = 2908 tons, including the test car. Train length = 2400 ft. Center of mass 1200 ft. back of measuring drawbar. 63 cars: 10 empty, 53 loaded. Kind of cars: 18 box, 38 gondola, 3 flat, 2 tank, 1 test, 1 caboose. Average weight per car = 46.16 tons.

1	2	3	4	5	6	7	8	9	10	11	12	13
Method	Item	Mile Post	Section Length	Pull P	Accel. A	Speed V_1	Speed V_2	Grade G	Direction	Velocity	Speed V	Resistance R
Point Columns 5, 6, and 9 to 13 show Momentary Values	7	106.79		10500	+0.0362			—16.70	+75°R	13	26.60	6.55
	8	105.82		10800	—0.0056			— 6.60	+80°R	15	29.90	6.74
	9	105.74		12050	—0.0172			— 3.96	+80°R	15	29.60	7.26
	10	104.65		18650	—0.0490			+15.80	+65°R	16	23.25	5.02
	11	104.59		19000	—0.0490			+16.05	+70°R	15	22.80	5.06
	12	104.53		20850	—0.0490			+16.30	+70°R	16	22.25	5.61
	13	104.41		21300	—0,0425			+15.20	+70°R	15	21.35	5.57
	14	104.32		21100	—0,0425			+14.10	+70°R	17	20.75	5.92
	15	104.21		21300	—0.0425			+14.08	+80°R	18	19.85	5.99
	16	104.10		21800	—0.0425			+16.90	+70°R	20	19.00	5.08
	17	103.62		28900	—0.0540			+28.60	+75°R	19	13.60	4.30
	18	103.50		30750	—0.0530			+29.50	+60°R	16	10.40	4.24
	19	103.72		27750	—0.0583			+27.90	+65°R	22	14.70	5.46
	20	105.40		12200	—0.0490			+ 5.94	+80°R	15	28.50	6.55
	21	104.82		17250	—0.0490			+11.90	+80°R	18	24.50	5.94
	22	106.84		10750	+0.0362			—17.40			26.40	6.90
	23	105.95		11500	+0.0156			—13.00			29.80	7.41
Section Columns 5, 6, and 9 to 13 show Average Values	7	107.04—106.73	1596	10850		25.44	26.92	—14.00	+75°R	12	26.20	7.03
	8	106.30—106.00	1588	11200		28.75	29.75	—13.20	+75°R	15	29.50	7.63
	9	106.00—105.70	1588	11150		29.75	29.75	— 6.60	+80°R	15	29.80	6.99
	10	105.70—105.40	1584	11650		29.75	28.40	+ 2.40	+80°R	15	29.00	6.29
	11	105.40—105.10	1592	13700		28.40	26.43	+ 6.07	+80°R	15	27.40	6.50
	12	105.10—104.80	1584	16500		26,43	24.32	+ 7.70	+80°R	18	25.40	6.66
	13	104.80—104.49	1588	18500		24.32	22.07	+13.20	+70°R	16	23.20	4.60
	14	104.49—104.19	1580	21350		22.07	19.80	+11.10	+70°R	16	20.90	6.16
	15	104.19—103.89	1576	22300		19.08	17.00	+13.50	+70°R	20	18.40	5.69
	16	103.89—103.59	1600	26600		17.00	12.95	+27.75	+65°R	22	15.00	3.87
	17	103 50—103.33	868	32500		11.52	8.45	+30.00			10.00	4.69
	18	103.33—103.21	648	35250		8.45	6.41	+30.00			7.40	3.99
	19	103.21—103.12	464	36750		6.41	4.50	+30.00			5.50	4.38
	20	103.12—103.03	512	37600		4.50	1.64	+30.00			3.00	3.94

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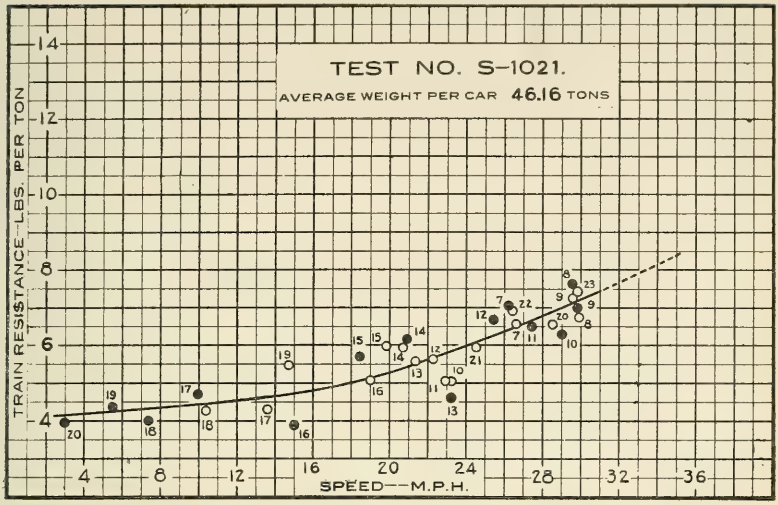
* For complete table heading see Table 36, p. 99.


TEST NO. S–1021.
AVERAGE WEIGHT PER CAR 46.16 TONS
TRAIN RESISTANCE—LBS. PER TON
14
12
10
8
6
4
SPEED—M.P.H.
4
8
12
16
20
24
28
32
36
20
19
18
17
18
17
19
16
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14
14
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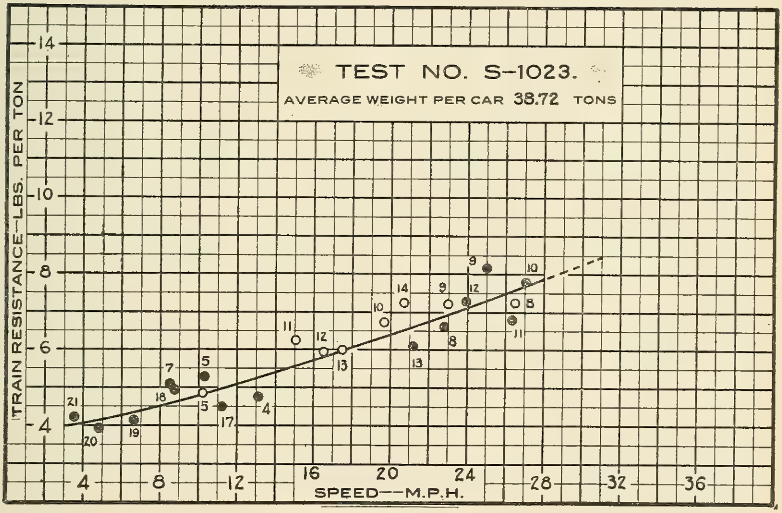
10

FIG. 25


TEST NO. S–1023.
AVERAGE WEIGHT PER CAR 38.72 TONS
TRAIN RESISTANCE—LBS. PER TON
14
12
10
8
6
4
SPEED—M.P.H.
4
8
12
16
20
24
28
32
36
21
20
19
7
18
5
5
17
4
11
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13
10
14
13
9
8
9
12
10
8
11

FIG. 26

TABLE 43 TEST NO. S–1023*

From Champaign to Paxton, May 23, 1908. Weather: Fair. Temperature: 62° F. at start, 74° F. at end of test. Total weight behind measuring drawbar = 2243 tons, including the test car. Train length = 2320 ft. Center of mass 1020 ft. back of measuring drawbar. 58 cars: 17 empty, 41 loaded. Kind of cars: 24 box, 30 gondola, 2 tank, 1 test, 1 caboose. Average weight per car = 38.72 tons.

1	2	3	4	5	6	7	8	9	10	11	12	13
Method	Item	Mile Post	Section Length	Pull P	Accel. A	Speed V_1	Speed V_2	Grade G	Direction	Velocity	Speed V	Resistance R
Point Columns 5, 6, and 9 to 13 show Momentary Values	5	114.00		18400	0			+ 8.88	+85° R	15	10.20	4.84
	8	106.71		10300	+0.0360			−16.00	+80° R	18	26.50	7.24
	9	104.91		12500	−0.0600			+10.70	+85° R	17	23.00	7.19
	10	104.48		17000	−0.0500			+16.03	−80° R	17	19.65	6.71
	11	103.98		20600	−0.0500			+20.30	+75° R	19	15.00	6.22
	12	104.04		19200	−0,0400			+17.80	−90° R	18	16.50	5.94
	13	104.12		18500	−0.0400			+16.00	−85° R	20	17.50	5.97
	14	104.67		14850	−0.0675			+15.28	+90° R	17	20.68	7.23
Section Columns 5, 6, and 9 to 13 show Average Values	4	116.50—116.00	2640	14700		13.10	13.10	+ 4.81	90° R	13	13.10	4.73
	5	114.71—114.21	2640	18600		10.30	10.30	+ 7.92	+85° R	15	10.30	5.30
	7	110.88—110.38	2240	29000		8.50	8.50	+20.70	+80° R	15	8.50	5.10
	8	108.95—108.56	2104	9700		23.86	21.45	+ 3.38	90° R	17	22.80	6.64
	9	107.21—106.71	2644	11250		23.60	26.43	−18.15	+80° R	18	25.05	8.18
	10	106.71—106.21	2616	10550		26.43	28.05	−14.30	+80° R	18	27.00	7.78
	11	105.47—105.17	1584	10850		27.27	25.10	+ 8.00	+85° R	25	26.30	6.78
	12	105.17—104,87	1580	12050		25.10	22.60	+ 9.01	+85° R	17	23.90	7.18
	13	104.87—104.57	1584	14450		22.60	19.65	+15.30	+85° R	17	21.20	6.07
	17	103.81—103.64	920	25650		11.86	9.28	+29.30			11.20	4.48
	18	103.64—103.50	716	28150		9.28	7.24	+28.75			8.72	4.92
	19	103.50—103.40	546	30000		7.24	5.46	+31.90			6.66	4.17
	20	103.40—103.32	394	31850		5.46	3.82	+34.20			4.80	3.93
	21	103.32—103.27	292	33200		3.82	2.59	+32.90			3.56	4.21

* For complete table heading see Table 36, p. 99.

TABLE 44 TEST NO. S-1027

From Champaign to Gilman, July 2, 1908. Weather: Intermittent rain. Temperature: 64° F. at start, 80° F. at end of test. Total weight behind measuring drawbar = 2185 tons, including the test car. Train length = 1710 ft. Center of mass 800 ft. back of measuring drawbar. 46 cars: 3 empty, 43 loaded. Kind of cars: 8 box, 35 gondola, 1 flat, 1 test, 1 caboose. Average weight per car = 47.44 tons.

1	2	3	4	5	6	7	8	9	10	11	12	13
						Speeds			Wind			
Method of Calculation	Item No.	Location on Road Milepost No.	Length of Section feet	Total Drawbar Pull pounds	Acceleration miles per hour per second	At Entrance to Section m. p. h.	At Exit from Section m. p. h.	Grade + Up — Down feet per mile	Approximate Direction	Approximate Velocity m. p. h.	Speed m. p. h.	Net Train Resistance pounds per ton
				P	*A*	*V*1	*V*2	*G*			*V*	*R*
Point Columns 5, 6, and 9 to 13 show Momentary Values	7	110.51		25900	0			+19.72	—50°R	9	9.50	4.37
	10	105.91		6900	0			— 9.16	90°R	13	34.00	6.63
	11	103.00		29700	—0.0054			+27.20	—55°R	5	8.20	3.81
	12	101.91		8100	0			— 6.54	90°R	17	28.10	6.16
	13	100.57		14400	0			+ 4.11	—70°R	15	14 50	5.00
	14	99.49		5300	0			— 9.56	—85°R	11	28.90	6.08
	16	97.10		3750	+0.0420			—22.90	—85°R	16	34.50	6.46
	17	86.03		10000	0			— 1.32	—70°R	22	22.30	5.06
Section Columns 5, 6, and 9 to 13 show Average Values	1	85.40— 86.30	2430	9900		22.30	22.30	— 1.09	—70°R	22	22.25	4.94
	2	87.85— 88.45	3215	6600		27.10	27.10	— 6.94	—75°R	15	27.00	5.65
	3	89.81— 90.56	3955	4500		31.25	31.25	— 9.22	—80°R	15	31.25	5 54
	4	115.56—116.17	3280	12800		19.00	19.00	+ 1.98	—60°R	12	18.90	5.11
	5	117.10—117.93	4440	11650		20.20	20.20	+ 0.27	—60°R	12	20.30	5.22
	7	106.11—105.51	3220	9400		33.40	32.85	— 4.09	90°R	13	33.75	6.33
	8	98.88—98.29	3080	9050		22.90	24.70	+ 7.55	+70°R	10	23.80	5.08
	9	97.61—96.72	4720	4200		31.90	34 25	—17.00	+85°R	16	33.87	6.09

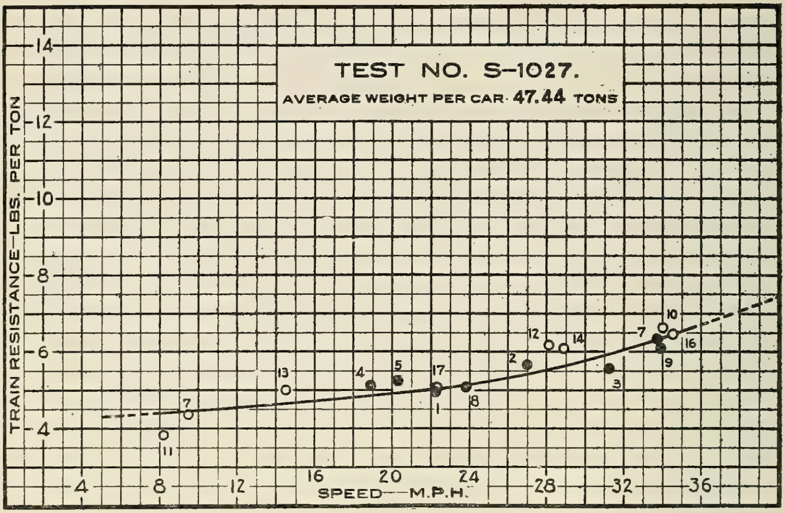
TEST NO. S–1027.
AVERAGE WEIGHT PER CAR 47.44 TONS
TRAIN RESISTANCE–LBS. PER TON
14
12
10
8
6
4
SPEED—M.P.H.
4
8
12
16
20
24
28
32
36
11
7
13
4
5
17
1
8
2
12
14
3
7
10
9
16

FIG. 27

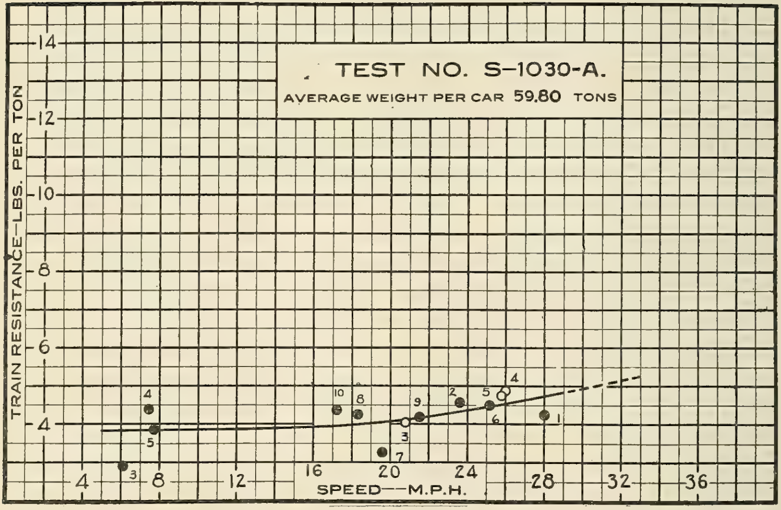
TEST NO. S–1030-A.
AVERAGE WEIGHT PER CAR 59.80 TONS
TRAIN RESISTANCE–LBS. PER TON
14
12
10
8
6
4
SPEED—M.P.H.
4
8
12
16
20
24
28
32
36
3
4
5
10
8
7
3
9
2
5
6
4
1

FIG. 28

TABLE 45 TEST NO. S-1030A

From Effingham to Mattoon, July 8, 1908. Weather: Fair. Temperature: 60° F. at start, 68° F. at end of the test. Total weight behind measuring drawbar = 2036 tons, including the test car. Train length = 1380 ft. Center of mass 690 ft. back of measuring drawbar. 34 cars: 2 empty, 32 loaded. Kind of cars: 32 gondola, 1 test, 1 caboose. Average weight per car = 59.88 tons.

1	2	3	4	5	6	7	8	9	10	11	12	13
						Speeds			Wind			
Method of Calculation	Item No.	Location on Road Milepost No.	Length of Section feet	Total Drawbar Pull pounds	Acceleration miles per hour per second	At Entrance to Section m. p. h.	At Exit from Section m. p. h.	Grade + Up — Down feet per mile	Approximate Direction	Approximate Velocity m. p. h.	Speed m. p. h.	Net Train Resistance pounds per ton
				P	A	V_1	V_2	G			V	R
Point Columns 5, 6, and 9 to 13 show Momentary Values	3	190.35		13200	—0.0690			+23.40	+50°R	8	20.80	4.04
	4	193.16		9050	—0.1350			+32.10	+55°R	9	26.03	4.90
	5	193.61		11000	+0.1390			—32.40	+60°R	5	25.80	4.77
Section Colums 5, 6, and 9 to 13 show Average Values	1	174.50—173.88	3280	160		26.20	30.00	—22.70	+20°R	6	28.00	4.23
	2	175.00—174.50	2600	5620		20.71	26.20	—22.70	+20°R	6	23.60	4.57
	3	176.97—176.70	3500	30050		6.54	6.00	+31.50	+20°R	3	6.12	2.91
	4	177.58—176.97	3212	30650		10.22	6.54	+31.50	+20°R	3	7.44	4.39
	5	178.00—176.70	8956	28800		16.15	6.00	+31.50	+20°R	3	7.65	3.87
	6	181.50—180.37	5144	12050		23.92	26.10	0	+50°R	7	25.20	4.46
	7	190.01—189.36	3452	12000		19.20	20.05	+ 5.10	+55°R	9	19.60	3.29
	8	191.72—191.44	1576	15000		17.18	19.14	0	+55°R	8	18.30	4.25
	9	193.16—192.71	2360	11550		26.03	17.58	+32.10	+60°R	5	21.50	4.20
	10	196.19—195.81	2140	14900		17.30	17.18	+ 7.70	+65°R	6	17.20	4.39

TABLE 46 TEST NO. S-1030B*

From Mattoon to Champaign, July 8, 1908. Weather: Fair. Temperature: 68° F. at start, 72° F. at end of test. Total weight behind measuring drawbar = 2312 tons, including the test car. Train length = 1650 ft. Center of mass 900 ft. back of measuring drawbar. 41 cars: 3 empty, 38 loaded. Kind of cars: 6 box, 33 gondola, 1 test, 1 caboose. Average weight per car = 57.12 tons.

1	2	3	4	5	6	7	8	9	10	11	12	13
Method	Item	Mile Post	Section Length	Pull P	Accel. A	Speed V_1	Speed V_2	Grade G	Direction	Velocity	Speed V	Resistance R
Point Columns 5, 6, and 9 to 13 show Momentary Values	3	167.46		7200	0			−1 .92			26.60	3.80
	5	165.52		6500	0			−3 .20			28.90	3.97
	6	164.45		8060	0			−2 .88	+20°R	12	28.40	4.53
	9	159.74		13900	0			+5 .12	+20°R	7	15.25	4.00
	10	157.80		18100	+0.0356			+5 .12	+25°R	6	12.30	4.23
	11	157.75		17000	+0.0356			+1 .12	+25°R	6	13.00	3.50
	12	157.57		16200	+0.0356			−0 .54	+35°R	6	14.20	3.93
	13	158.06		23600	+0.0457			+5 .60	+65°R	3	8.30	3.70
	14	157.94		21500	+0.0457			+2 .56	+30°R	5	10.70	3.96
	21	164.15		7200	+0.0700			−21.10	+30°R	9	28.50	4.48
Section Columns 5, 6 and 9 to 13 show Average Values	1	166.62—167.06	2315	8000		25.80	25.80	−2.12			25.50	4.22
	2	164.45—164.95	3164	7350		27.40	27.00	−0.84	+20°R	12	27.15	3.93
	3	158.72—159.25	2815	2500		17.30	17.30	−7.82	+65°R	4	16.90	4.02
	4	155.44—154.81	3300	7550		27.10	28.90	−8.96	+20°R	12	28.10	4.52
	5	152.25—152.88	3270	14200		17.50	17.50	+6.14			17.00	3.73
	6	149.04—148.20	4396	11800		21.40	23.00	−0.66			22.20	4.18
	7	143.32—143.92	3150	14000		16.30	16.30	+5.48			16.60	3.91
	8	140.49—141.23	3912	11950		19.63	19.25	+3.77			19.75	3.89
	9	132.65—131.68	5084	8500		26.75	25.26	0			26.05	4.68
	10	145.06—144.48	3068	16950		12.48	13.63	+7.65			13.10	3.65
	11	158.06—157.80	1400	20850		8 46	12.55	+3.40	+65°R	3	10.60	3.41
	12	157.80—157.57	1200	17500		12.55	14.58	+0.66	+25°R	6	13.70	4 08
	13	162.33—161.87	2416	8730		23.70	24.40	−4.36	+20°R	9	23.50	3.59
	14	149.65—148.97	3280	12400		21.53	21.30	+4.20			21.30	3.87

* For complete table heading see Table 36, p. 99.

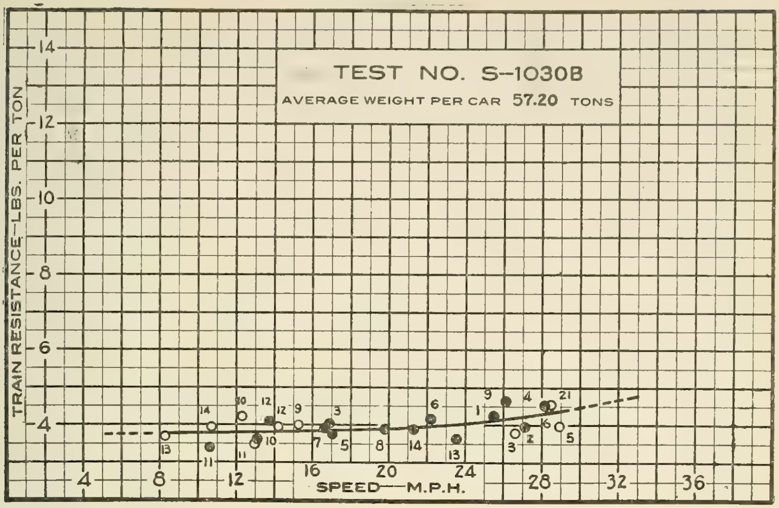
TEST NO. S–1030B
AVERAGE WEIGHT PER CAR 57.20 TONS
TRAIN RESISTANCE–LBS. PER TON
14
12
10
8
6
4
SPEED—M.P.H.
4
8
12
16
20
24
28
32
36

FIG. 29

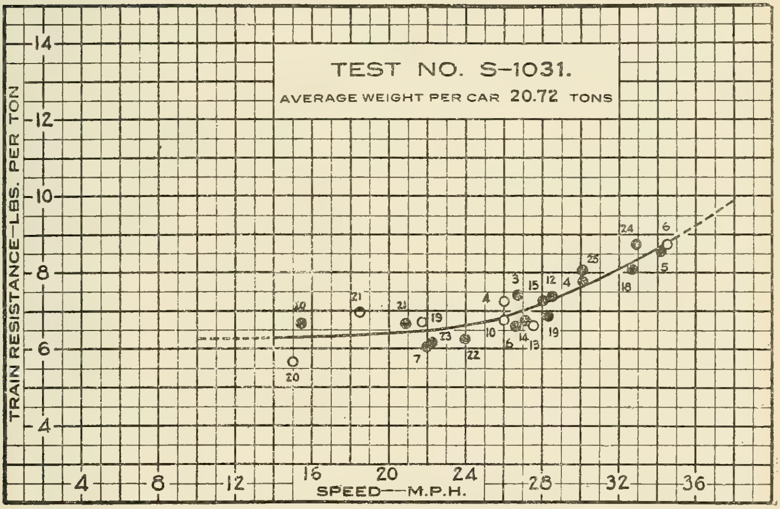
TEST NO. S–1031.
AVERAGE WEIGHT PER CAR 20.72 TONS
TRAIN RESISTANCE–LBS. PER TON
14
12
10
8
6
4
SPEED—M.P.H.
4
8
12
16
20
24
28
32
36

FIG. 30

TABLE 47 TEST NO. S-1031*

From Champaign to Dorans, July 22, 1908. Weather: Fair. Temperature: 70° F. at start, 82° F. at end of test. Total weight behind measuring drawbar = 747 tons, excluding the test car. Train length = 1425 ft. Center of mass 1000 ft. back of measuring drawbar. 36 cars: 30 empty, 6 loaded. Kind of cars: 33 box, 1 gondola, 1 flat, 1 caboose. Average weight per car = 20.72 tons.

1	2	3	4	5	6	7	8	9	10	11	12	13
Method	Item	Mile Post	Section Length	Pull P	Accel. A	Speed V_1	Speed V_2	Grade G	Direction	Velocity	Speed V	Resistance R
Point Columns 5, 6, and 9 to 13 show Momentary Values	4	142.06		4700	−0.0204			− 1.50	+ 0°	5	26,00	7.25
	6	147.10		2600	0			−13.84	+ 0°	7	34.50	8.73
	10	159.81		4200	0			− 3.01	+ 0°	6	26.00	6.76
	13	163.09		4400	0			− 1.89	+ 0°	7	27,50	6.60
	19	166.83		7900	0			+10.20	+ 0°	2	21.75	6 70
	20	164.40		12400	+0.0275			+21.80	+40°L	4	15.00	5.68
	21	164.75		9650	+0.0550			+ 1.50	+40°L	4	18.50	6.95
Section Columns 5, 6, and 9 to 13 show Average Values	3	139.57—140 36	4180	4350		26.70	26.70	− 4.13	+ 0°	5	26.70	7.40
	4	143.90—144.25	4460	3900		29.75	29.75	− 6.81	+ 0°	5	30.10	7.76
	5	146.68—147.51	4405	2500		33.90	33.90	−13.65	+ 0°	7	34.20	8.53
	6	151.94—152.77	4390	4950		26.60	26.60	+ 0.18	+ 0°	4	26.60	6.56
	7	155.70—156.45	4016	7100		22.00	22.00	+ 9.60	+ 0°	4	22.00	6.01
	12	149.00—149.53	2760	4650		28.36	27.77	− 0,77	+ 0°	7	28.50	7.36
	14	153.88—154.74	4568	4380		27.61	25.62	+ 2.14	+ 0°	5	27.10	6.72
	15	160.31—160.78	2468	4450		25.95	28.94	−16.15	+ 0°	7	28.00	7.24
	18	147.51—148.35	4412	2900		33 53	31.36	− 5.04	+ 0°	7	32.70	8.07
	19	153.20—153.87	3528	4470		28.30	28.30	− 2.25	+ 0°	5	28.30	6.85
	20	164.40—164.74	1812	11800		15.00	18.00	+13.70	+ 0°	1	15.40	6.69
	21	164.74—165.50	3980	7700		18.00	22.75	+ 0.40	+ 0°	1	20.90	6.65
	22	159.63—159.16	2464	5500		24.80	23.65	+ 7.30	+ 0°	5	24.00	6.22
	23	157.40—158.36	5064	5450		22.60	23.85	+ 0.94	+ 0°	5	22.30	6.11
	24	146.17—146.68	2652	3000		31.90	33.50	−19.90	+ 0°	7	32.90	8.74
	25	161.24—161.62	2014	4100		30.50	30.50	− 6.84	+ 0°	6	30.50	8.09

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* For complete table heading see Table 36, p. 99.

TABLE 48 TEST NO. S-1033*

From Champaign to Gilman, Sept. 26, 1908. Weather: Fair. Temperature: 66° F. at start, 82° F. at end of test. Total weight behind measuring drawbar = 2275 tons, including the test car. Train length = 1710 ft. Center of mass 850 ft. back of measuring drawbar. 44 cars: 2 empty, 42 loaded. Kind of cars: 42 gondola, 1 test, 1 caboose. Average weight per car = 51.70 tons.

1	2	3	4	5	6	7	8	9	10	11	12	13
Method	Item	Mile Post	Section Length	Pull P	Accel. A	Speed V_1	Speed V_2	Grade G	Direction	Velocity	Speed V	Resistance R
Point Columns 5, 6, and 9 to 13 show Momentary Values	9	111.08		26050	0			+20.20	+0°	5	8.15	3.79
	10	110.72		25150	0			+19.45	+0°	5	9.75	3.68
	12	104.13		23900	0			+16.98	+5° R	7	12.00	4.07
	13	98.18		6000	+0.1066			—31.50	+5° L	12	29.35	4.26
	17	93.63		2700	0			— 9.88	+5° R	12	40.00	4.93
	18	90.42		3850	0			—10.49	+5° L	17	39.40	5.67
	20	85.88		6450	0			— 4.02	+0°	16	31.75	4.35
	21	83.40		6800	0			— 3.40	+5° L	15	31.75	4.28
Section Columns 5, 6, and 9 to 13 show Average Values	2	118.27—117.19	5688	11300		23.60	24.10	+ 0.28	+15° R	7	24.25	4.57
	3	111.30—110.60	3684	25900		8.98	8.98	+20.20	+ 0°	5	8.98	3.72
	4	104.91—103.91	5260	24000		11.21	11.21	+16.30	+ 5° R	7	11.21	4.37
	5	101.66—100.97	3660	12400		22.85	18.75	+10.96	+10° R	15	20.79	4.50
	6	98.19— 97.14	5512	5000		29.20	37.25	—25.87	+ 5° L	14	34.17	5.33
	7	94.07— 93.24	4400	3200		40.00	40.00	— 9.24	+ 5° R	12	40.00	4.91
	8	96.25— 95.58	3556	3200		37.85	42.10	—28.80	+ 5° L	22	40.40	5.78
	9	90.66— 90.00	3492	4150		38.95	39.85	—10.43	+ 5° L	17	39.68	4.38
	10	89.24— 88.76	2504	4950		38.30	37.40	— 1.90	+ 5° L	10	37.94	4.77
	11	83.80— 83.40	2096	6600		31.25	31.58	— 5.04	+ 5° R	14	31.75	4.19
	12	116.00—115.36	3400	11800		23.00	22.40	+ 3.99	+ 5° R	7	23.20	4.23
	13	114.67—114.27	2108	14800		19.50	18.85	+ 8.55	+ 5° R	7	19.20	4.07
	14	103.91—103.11	2600	29900		10.72	5.81	+29.20	+ 5° R	7	6.33	4.20
	15	97.14— 96.25	4700	4200		37.50	38.00	—10.80	+ 5° L	22	37.70	5.40
	16	83.80— 83.05	3930	2900		32.05	31.10	5.78	+ 0°	15	31.50	4.53
	17	88.77— 88.00	4076	5200		37.53	37.05	5.12	+ 5° L	17	37.30	4.84

* For complete table heading, see Table 36, p. 99.

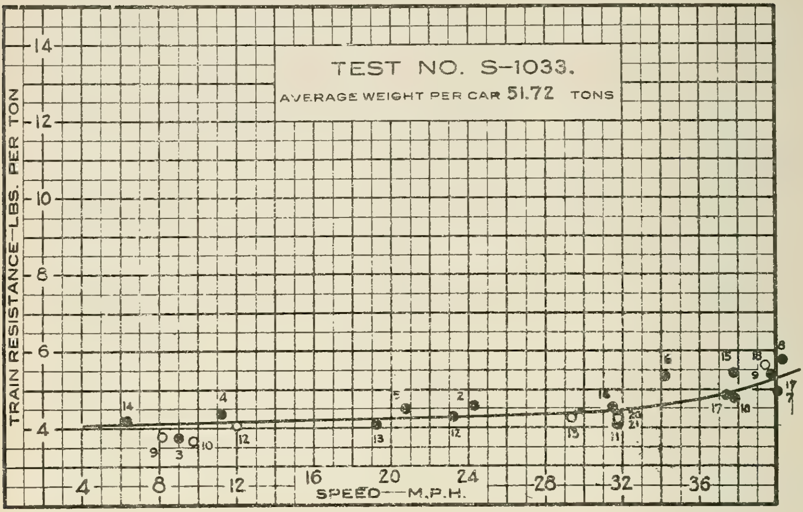
TEST NO. S–1033.
AVERAGE WEIGHT PER CAR 51.72 TONS
TRAIN RESISTANCE—LBS. PER TON
SPEED—M.P.H.
4
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FIG. 31

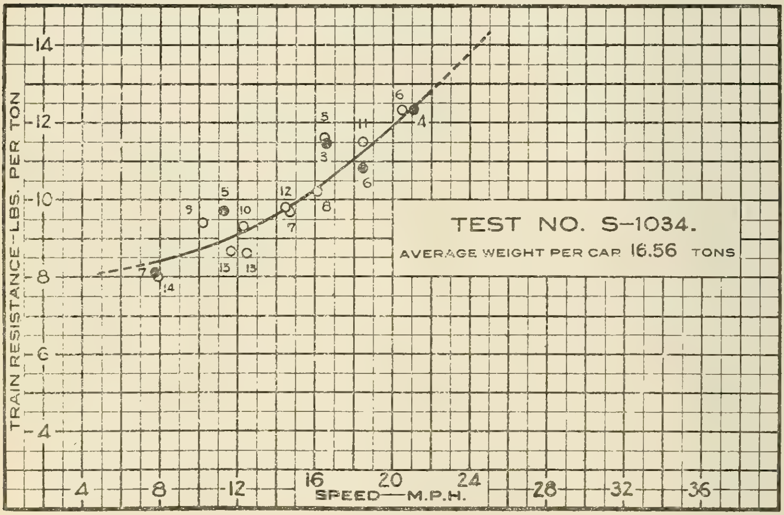
TEST NO. S–1034.
AVERAGE WEIGHT PER CAR 16.56 TONS
TRAIN RESISTANCE—LBS. PER TON
SPEED—M.P.H.
4
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FIG. 32

TABLE 49 TEST NO. S-1034

From Champaign to Mattoon, October 3, 1908. Weather: Fair. Temperature: 42° F. at start, 60° F. at end of test. Total weight behind measuring drawbar = 1259 tons, excluding the test car. Train length = 3015 ft. Center of mass 1500 ft. back of measuring drawbar. 76 cars: 76 empty, 0 loaded. Kind of cars: 75 gondola, 1 caboose. Average weight per car =16.56 tons.

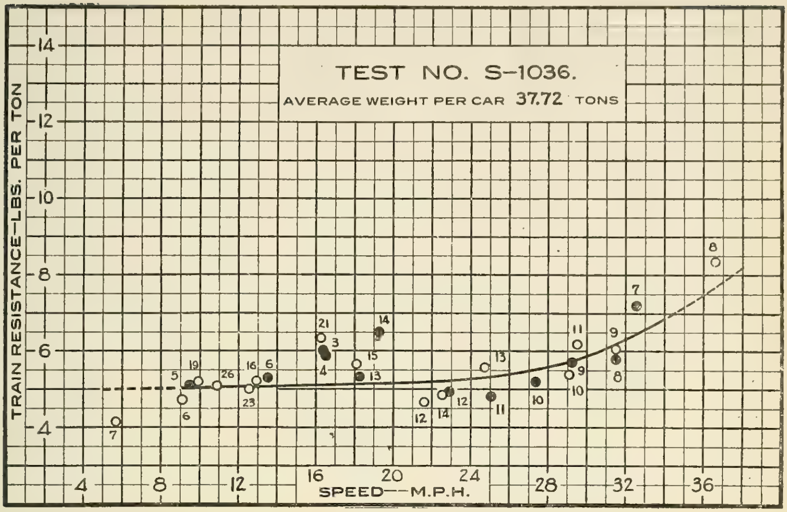
1	2	3	4	5	6	7	8	9	10	11	12	13
Method of Calculation	Item No.	Location on Road	Length of Section feet	Total Drawbar Pull pounds	Acceleration miles per hour per second	Speeds		Grade + Up — Down feet per mile	Wind		Speed m. p. h.	Net Train Resistance pounds per ton
		Milepost No.				At Entrance to Section m. p. h.	At Exit from Section m. p. h.		Approximate Direction	Approximate Velocity m. p. h.		
				P	*A*	*V*1	*V*2	*G*			*V*	*R*
Point Columns 5, 6, and 9 to 13 show Momentary Values	5	143.80		10000	0			— 9.64	—55°L	5	16.50	11.59
	6	146.89		7900	0			—15.94	—80°L	5	20.50	12.28
	7	149.30		11800	0			— 0.84	—55°L	4	14.70	9.70
	8	153.44		10300	0			— 5.25	—80°L	2	16.10	10.17
	9	156.22		16440	0			+ 9.52	—30°L	3	10.25	9.45
	10	159.72		14400	0			+ 5.52	+85°L	1	12.25	9.35
	11	161.05		9150	0			—12.20	— 0°	1	18.25	11.49
	12	165.81		13000	0			+ 1.40	—50°L	5	14.50	9.79
	13	166.80		15550	0			+ 9.81	—75°L	3	12.25	8.62
	14	168.45		17600	0			+15.75	—60°L	4	7.90	8.00
	15	167.93		12500	0			+ 3.41	90°L	5	11.60	8.65
Section Columns 5, 6, and 9 to 13 show Average Values	3	142.97—143.80	4373	10700		15.60	16.50	— 9.48	—55°L	5	16.56	11.45
	4	146.40—147.54	6027	7800		21.00	21.00	—16.12	—80°L	5	21.10	12.31
	5	154.78—155.70	4878	16000		11.25	11.25	+ 7.96	—45°L	5	11.27	9.69
	6	160.77—161.53	4058	9100		17.50	17.50	— 9.37	+85°L	4	18.44	10.78
	7	168.22—168.74	2744	18000		7.25	7.90	+15.57	—60°L	4	7.80	8.12

TABLE 50 TEST NO. S-1036*

From Champaign to Gilman, October 10, 1908. Weather: Fair. Temperature: 40° F. at start, 62° F. at end of test. Total weight behind measuring drawbar — 1961 tons, including the test car. Train length = 2010 ft. Center of mass 966 ft. back of measuring drawbar. 52 cars: 8 empty, 44 loaded. Kind of cars: 36 box, 13 gondola, 1 flat, 1 test, 1 caboose. Average weight per car = 37.72 tons.

1	2	3	4	5	6	7	8	9	10	11	12	13
Method	Item	Mile Post	Section Length	Pull P	Accel. A	Speed V_1	Speed V_2	Grade G	Direction	Velocity	Speed V	Resistance R
Point Columns 5, 6, and 9 to 13 show Momentary Values.	6	111.03		24350	0			+20.30	—15°R	5	9.14	4.71
	7	103.06		30450	0			+30.10	—45°R	3	5.73	4.12
	8	95.32		3300	0			—17.60	+70°R	11	36.65	8.35
	9	93.75		3200	0			—11.55	+75°R	8	31.50	6.01
	10	92.16		1800	0			—11.80	+80°R	7	29.15	5.39
	11	90.02		5500	0			— 8.90	+55°R	7	29.50	6.17
	12	86.10		8750	0			— 0.50	+25°R	3	21.60	4.65
	13	83.51		7400	0			— 4.70	+15°R	5	24.75	5.55
	14	81.38		5800	0			— 5.00	+35°R	4	22.50	4.85
	15	104.14		14800	—0.0440			+16.03	—65°R	5	18.14	5.65
	16	103.67		20150	—0.0620			+28.90	—40°R	9	12.90	5.20
	19	111.20		23900	—0.0260			+24.96	—15°R	4	9.90	5.19
	21	117.18		11800	0			+ 0.79	—50°R	4	16.23	6.32
	23	114.26		15100	—0.0070			+ 8.93	—60°R	5	12.54	4.99
	26	103.62		23450	—0.0440			+29 16	—35°R	10	10.90	5.07
Section Columns 5, 6, and 9 to 13 show Average Values	3	118.27—117.73	2888	11850		16.41	16.41	+ 0.18	—50°R	4	16.41	5.98
	4	117.73—117.18	2904	11750		16.50	16.50	+ 0.36	—50°R	4	16.50	5.86
	5	111.20—110.68	2768	23900		9.44	9.44	+18.70	—15°R	4	9.44	5.09
	6	101.46—101.01	2372	17350		14.45	12.82	+12.91	—75°R	5	13.48	5.26
	7	96.30— 95.71	3100	4600		30.40	34.50	—28.45	+80°R	8	32.50	7.19
	8	94.14— 93.40	3924	3300		30.95	31.25	—11.70	+75°R	7	31.48	5.78
	9	90.51— 90.02	2572	5850		28.80	29.50	— 9.96	+70°R	6	29.25	5.64
	10	89.18— 88.72	2412	6200		27.75	26.95	— 1.97	+65°R	5	27.42	5.18
	11	83.72— 82.99	3856	7250		24.50	25.75	— 5.89	+25°R	6	25.03	4.80
	12	81.19— 81.64	2348	6200		22.86	22.86	— 4.72	+35°R	4	22.86	4.95
	13	104.61—103.13	3884	14700		21.53	14.85	+17.00	+65°R	5	18.25	5.30
	14	109.85—109.10	3972	11600		15.17	23.90	—17.22	+70°R	1	19.30	6.47

* For complete table heading see Table 36, p. 99.


TEST NO. S–1036.
AVERAGE WEIGHT PER CAR 37.72 TONS
TRAIN RESISTANCE—LBS. PER TON
14
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SPEED—M.P.H.
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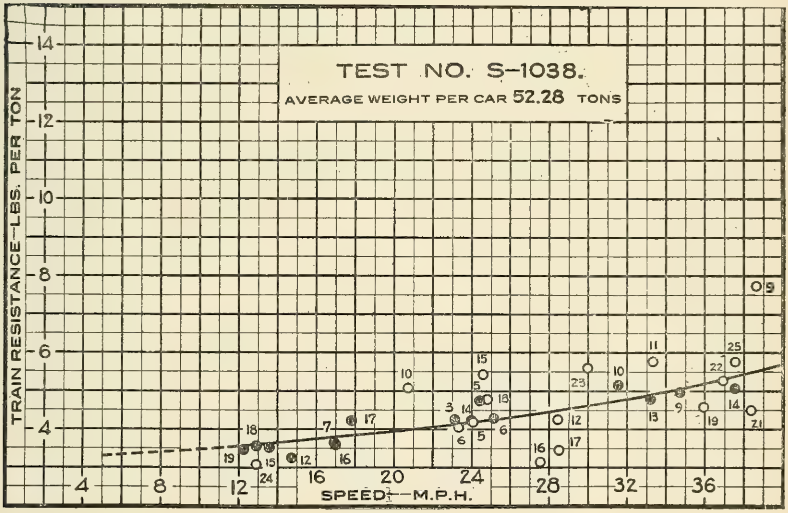
Fig. 33


TEST NO. S–1038.
AVERAGE WEIGHT PER CAR 52.28 TONS
TRAIN RESISTANCE—LBS. PER TON
14
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8
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4
SPEED—M.P.H.
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Fig. 34

TABLE 51 TEST NO. S-1038*

From Champaign to Gilman, October 15, 1908. Weather: Fair. Temperature: 58° F. at start, 72° F. at end of test. Total weight behind measuring drawbar = 2144 tons, including the test car. Train length = 1650 ft. Center of mass 825 ft. back of measuring drawbar. 41 cars: 3 empty, 38 loaded. Kind of cars: 7 box, 32 gondola, 1 test, 1 caboose. Average weight per car = 52.28 tons.

1	2	3	4	5	6	7	8	9	10	11	12	13
Method	Item	Mile Post	Section Length	Pull P	Accel. A	Speed V_1	Speed V_2	Grade G	Direction	Velocity	Speed V	Resistance R
Point Columns 5, 6, and 9 to 13 show Momentary Values	5	117.32		9800	0			+ 0.96	+15°L	16	24.00	4.21
	6	115.84		10400	0			+ 2.08	+15°L	16	23.15	4.06
	7	113.84		14350	0			+ 8.01	+15°L	13	16.90	3.65
	9	106.00		5500	0			—13.60	+20°L	20	38.60	7.72
	10	100.53		13200	0			+ 2.85	+15°L	15	20.75	5.07
	11	99.29		8150	0			+ 5.18	+20°L	19	33.30	5.76
	12	93.18		8300	0			— 0.96	+ 5°L	18	28.40	4.24
	14	89.55		10200	0			+ 1.44	+20°L	17	24.00	4.21
	15	88.74		10100	0			— 1.85	+20°L	17	24.60	5.41
	16	87.71		9000	0			+ 2.78	+15°L	19	27.50	3.14
	17	87.04		8450	0			+ 1.28	+ 5°L	20	28.50	3.45
	18	86.42		10750	0			+ 0.61	+10°L	16	24.80	4.77
	19	97.86		6800	+0.0984			—28.15	+20°L	17	35.92	4.60
	21	97.54		3350	+0.0699			—24.95	+15°L	19	38.35	4.46
	22	97.76		6200	+0.0880			—28.15	+20°L	18	36.90	5.29
	23	98.90		9050	—0.0802			+16.30	+25°L	16	29.95	5.57
	24	103.05		22800	—0.0370			+29.10	+ 5°L	9	12.85	3.09
	25	105.90		5500	0.			— 8.42	+20°L	18	37.55	5.76
Section Columns 5, 6, and 9 to 13 show Average Values	3	117.06—118.18	5935	10000		23.65	24.15	+ 0.43	+15°L	16	23.12	4.23
	5	88.74— 89.55	4260	10250		24.20	24.75	— 0.95	+20°L	17	24.20	4.71
	6	85.84— 86.36	2768	10250		25.10	25.90	— 1.33	+10°L	16	25.15	4.28
	9	98.24— 97.76	2544	7100		31.95	36.90	—28.65	+20°L	16	34.69	4.97
	10	99.29— 98.90	2080	8100		32.80	29.95	+11.92	+20°L	17	31.51	5.14
	12	103.44—103.05	2050	19200		18.75	12.85	+31.70	+ 5°L	11	14.70	3.22
	13	105.18—104.58	3168	6850		35.10	30.60	+12.66	+15°L	17	33.20	4.78
	14	106.26—105.48	4120	6050		36.40	36.40	— 5.92	+20°L	18	37.50	5.06
	15	111.10—110.65	2384	20150		14.75	13.55	+18.04	+20°L	11	13.53	3.54
	16	110.24—109.82	2236	17050		15.00	19.75	— 1.89	+15°L	15	16.94	3.61
	17	114.74—114.24	2608	13750		18.70	17.80	+ 8.10	+15°L	13	17.80	4.22
	18	111.10—110.24	4536	20650		14.30	14.30	+15.95			12.85	3.59
	19	110.65—110.25	2152	21400		12.80	14.30	+13.73			12.22	3.48

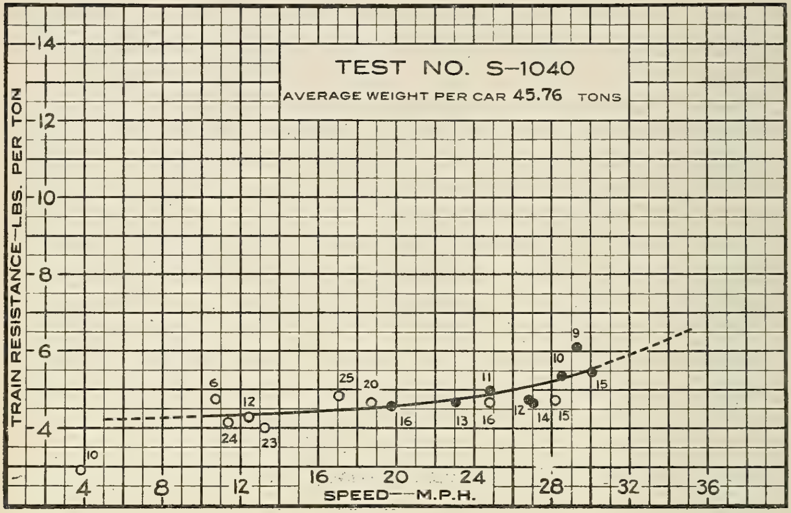
*For complete table heading see Table 36, p. 99.

TABLE 52 TEST NO. S–1040

From Champaign to Gilman, October 24, 1908. Weather: Intermittent rain. Temperature: 57° F. at start, 53° F. at end of test. Total weight behind measuring drawbar = 2152 tons, including the test car. Train length = 1830 ft. Center of mass 900 ft. back of measuring drawbar. 47 cars: 2 empty, 45 loaded. Kind of cars: 21 box, 23 gondola, 1 tank, 1 test, 1 caboose. Average weight per car = 45.76 tons.

1	2	3	4	5	6	7	8	9	10	11	12	13
Method	Item	Mile Post	Section Length	Pull P	Accel. A	Speed V_1	Speed V_2	Grade G	Direction	Velocity	Speed V	Resistance R
Point Columns 5, 6, and 9 to 13 show Momentary Values	6	114.68		16500	0			+ 7.72	+40° R	8	10.77	4.75
	10	102.99		28100	0			+27.10	+20° R	8	3.82	2.92
	12	100.64		15100	0			+ 7.22	+35° R	10	12.45	4.28
	15	88.71		8900	0			1.53	+20° R	13	28.20	4.71
	16	86.32		9850	0			— 0.26	+15° R	11	24.82	4.67
	20	101.55		8900	—0.0441			+ 9.53	+35° R	13	18.72	4.66
	23	100.85		13600	—0.0194			+10.97	+30° R	10	13.25	3.99
	24	103.48		23000	—0.0511			+30.00	+40° R	10	11.40	4.13
	25	108.45		13200	—0.0255			+ 9.81	+35° R	11	17.05	4.82
Section Columns 5 and 9 to 13 show Average Values	9	90.52— 90.03	2584	8500		28.70	29.62	— 9.61	+25° R	13	29.36	6.14
	10	89.29— 88.52	3768	8750		28.80	28.20	— 1.64	+20° R	13	28.54	5.33
	11	86.32— 95.91	2180	10150		24.62	24.62	— 0.70	+15° R	11	24.77	4.98
	12	83.83— 83.16	3548	7000		26.70	27.10	— 4.99	+15° R	12	26.88	4.72
	13	93.64— 93.20	2200	4000		22.37	21.74	— 5.04	+26° R	12	23.10	4.64
	14	83.83— 83.00	4360	7250		26.70	27.80	— 5.82	+15° R	12	27.00	4.64
	15	106.10—105.70	1988	7450		29.20	29.85	— 8.76	+25° R	13	30.10	5.45
	16	103.87—104.64	4056	15100		22.75	16.70	+17.20	+20° R	9	19.75	4.56

* For complete table heading see Table 36, p. 99.


TEST NO. S-1040
AVERAGE WEIGHT PER CAR 45.76 TONS
TRAIN RESISTANCE—LBS. PER TON
14
12
10
8
6
4
SPEED—M.P.H.
4
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12
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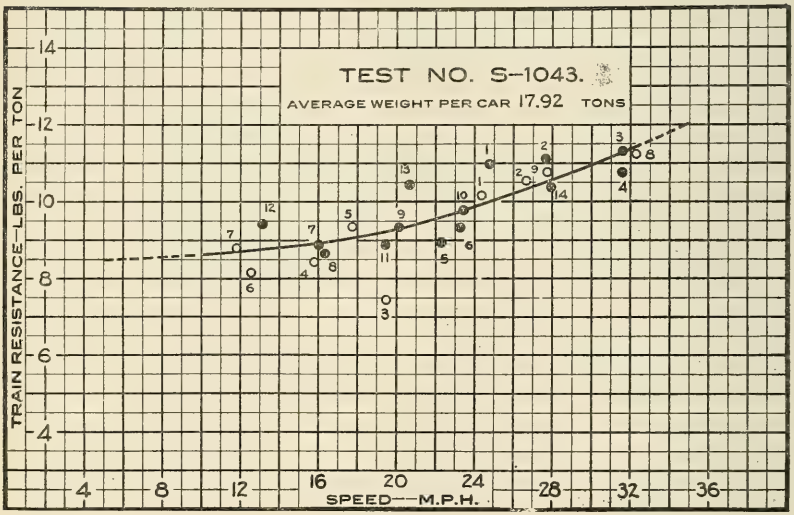
FIG. 35


TEST NO. S-1043.
AVERAGE WEIGHT PER CAR 17.92 TONS
TRAIN RESISTANCE—LBS. PER TON
14
12
10
8
6
4
SPEED—M.P.H.
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12
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20
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28
32
36
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12
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FIG. 36

TABLE 53 TEST NO. S–1043*

From Champaign to Mattoon, November 7, 1908. Weather: Clear. Temperature: 38° F. at start, 53° F. at end of test. Total weight behind measuring drawbar = 1118 tons, excluding the test car. Train length = 2580 ft. Center of mass 1300 ft. back of measuring drawbar. 66 cars: 65 empty, 1 loaded. Kind of cars: 15 box, 49 gondola, 1 tank, 1 caboose. Average weight per car = 16.92 tons.

1	2	3	4	5	6	7	8	9	10	11	12	13
Method	Item	Mile Post	Section Length	Pull P	Accel. A	Speed V_1	Speed V_2	Grade G	Direction	Velocity	Speed V	Resistance R
Point Columns 5, 6, and 9 to 13 show Momentary Values	1	142.05		11300	0			− 0.14	+25° R	8	24.35	10.15
	2	143.25		9400	+0.0124			− 8.80	+20° R	11	26.70	10.51
	3	150.77		11000	+0.0165			+ 2.00	+25° R	7	19.50	7.43
	4	156.10		13300	0			+ 9.21	+20° R	6	15.80	8.41
	5	157.78		11700	0			+ 2.97	+ 5° R	7	17.75	9.33
	6	168.23		15100	0			+14.13	+65° R	4	12.55	8.14
	7	168.78		17000	+0.0106			+14.21	+55° R	4	11.80	8.76
	8	147.29		7400	0			−12.11	+15° R	13	32.30	11.21
	9	143.90		8650	0			− 7.96	+10° R	11	27.75	10.75
Section Columns 5 and 9 to 13 show Average Values	1	139.25—140.49	6540	10500		24.70	25.50	− 3.97	+30° R	8	24.76	10.97
	2	143.70—144.40	3652	8800		27.96	26.87	− 5.12	+15° R	11	27.67	11.01
	3	146.20—147.52	6960	7500		29.43	32.10	−16.61	+ 5° R	13	31.60	11.29
	4	147.52—148.31	4172	7600		32.10	30.42	− 5.50	+ 5° R	13	31.60	10.72
	5	151.00—152.47	7832	11100		20.00	22.50	− 0.03	+15° R	9	22.25	8.93
	6	152.47—153.45	5112	9450		22.50	23.90	− 4.70	+25° R	10	23.24	9.31
	7	155.27—156.20	4952	13350		16.33	15.75	+ 9.02	+20° R	6	16.07	8.79
	8	156.20—157.16	5028	13850		15.75	17.00	+ 8.34	+20° R	6	16.32	8.63
	9	159.65—166.66	5316	10620		18.60	22.75	− 5.94	+15° R	8	20.13	9.41
	10	160.66—162.22	8248	8500		22.75	20.90	− 3.84	+15° R	8	23.43	9.76
	11	165.74—166.74	5276	11600		20.25	18.02	+ 7.04	+50° R	7	19.45	8.88
	12	168.43—169.53	5792	15400		12.40	16.27	+ 8.20	+55° R	4	13.16	9.40
	13	169.53—170.72	6272	11400		16.27	22.15	− 7.87	+15° R	9	20.70	10.41
	14	145.58—146.20	3276	9150		26.90	29.40	−13.96	+ 5° R	11	27.94	10.35

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* For complete table heading see Table 36, p. 99.

TABLE 54 TEST NO. S-1048*

From Champaign to Ludlow, November 28, 1908. Weather: Fair. Temperature: 36° F. at start, 39° F. at end of test. Total weight behind measuring drawbar = (a)-2443 tons, (b)-2355 tons, including the test car. Train length = (a)-2175 ft. (b)-2100 ft. Center of mass 925 ft. back of measuring drawbar (a)-54 cars, (b)-52 cars, 8 empty, (a)-46 loaded. (b)-44 loaded. Kind of cars: 18 box (a)-34 gondola, (b)-32 gondola, 1 test, 1 caboose. Average weight per car = 45.24 tons. (a)—Champaign to Rantoul. (b)—Rantoul to Ludlow.

1	2	3	4	5	6	7	8	6	10	11	12	13
Method	Item	Mile Post	Section Length	Pull P	Accel. A	Speed V_1	Speed V_2	Grade G	Direction	Velocity	Speed V	Resistance R
Point Columns 5, 6, and 9 to 13 show Momentary Values	1	110.74		26750	0			+18.86	+ 5° L	5	9.35	4.21
	2	111.17		30150	0			+24.13	+ 5° L	5	7.78	3.65
	3	114.44		18200	0			+ 8.26	+25° L	6	14 00	4.33
	4	115.79		14200	0			+ 1.94	+30° L	6	18.36	5.08
	5	116.48		13550	0			+ 0.73	+25° L	7	19.36	5.27
	6	117.61		12800	0			0	+30° L	5	19.45	5.24
	7	118 43		13550	0			— 0.49	+ 5° L	6	19.73	5.74
	10	115.34		14800	—0.0229			+ 7.28	+30° L	6	17.36	5.46
	11	114.71		17800	—0.0053			+ 9.47	+25° L	6	14.27	4.20
	14	110.53		29350	0			+20.10	+ 5° L	5	8.73	4.84
	15	110.16		20950	+0.0388			+ 0.25	+10° L	6	11.73	5.16
	16	111.01		29850	+0.0123			+20.10	+ 5° L	5	8.28	3.89
	17	111.80		17800	—0.0900			+28.15	+15° L	5	16.45	5.37
	18	111.59		21950	—0.0652			+29.91	+15° L	5	12.00	4.15
	19	111.40		28550	—0.0352			+29.16	+15° L	5	9.10	4.39
	20	109.83		17400	+0.0405			— 4.78	+10° L	8	15.00	5.38
	21	111.51		25500	—0.0511			+29.91	+15° L	5	10.64	4.31
	22	109.09		9900	+0.0476			—19.35	+ 0°	9	24.20	7.05
	23	108.69		11000	—0 0405			+ 6.54	+ 5° R	9	23.91	6.01
	24	108.31		12200	—0.0493			+10.30	+ 5° R	9	21.30	5.92
	25	108.49		11200	—0.0511			+ 9.05	+ 5° R	9	23.00	6.15
Section Columns 5 and 9 to 13 show Average Values	5	118.42—117.61	4306	13400		19.73	19.45	0	+30° L	5	19.58	5.66
	6	115.94—115.34	3172	14650		18.27	17.36	+ 4.49	+30° L	6	18.02	5.00
	7	114.71—114.24	2476	18100		14.27	13.82	+ 8.11	+25° L	6	14.06	4.69
	9	111.40—110.61	4176	29000		9.10	9.10	+21.40	+ 5° L	5	8.50	4.19
	10	108.69—108.31	2008	11000		23.90	21 30	+ 9.21	+ 5° L	9	22.80	5.20
	11	112.06—111.40	3488	20000		20.82	9.10	+28.30	+15° L	5	13.98	4.72

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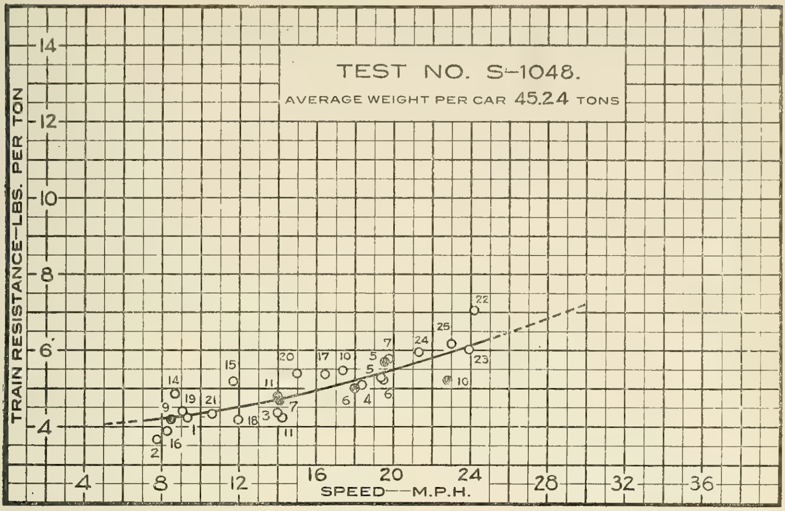
* For complete table heading see Table 36, p. 99.


TEST NO. S-1048.
AVERAGE WEIGHT PER CAR 45.24 TONS
TRAIN RESISTANCE—LBS. PER TON
14
12
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12
16
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24
28
32
36
SPEED—M.P.H.

FIG. 37

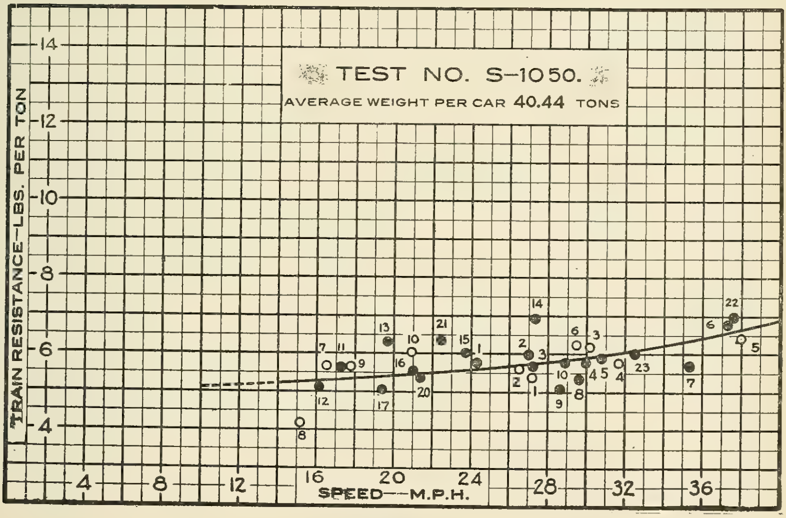
TEST NO. S-1050.
AVERAGE WEIGHT PER CAR 40.44 TONS
TRAIN RESISTANCE—LBS. PER TON
14
12
10
8
6
4
4
8
12
16
20
24
28
32
36
SPEED—M.P.H.

FIG. 38

TABLE 55 TEST NO. S-1050*

From Champaign to Mattoon, January 23, 1909. Weather: Fair. Temperature: 53° F. at start, 66° F. at end of test. Total weight behind measuring drawbar = 1618 tons, excluding the test car. Train length = 1620 ft. Center of mass 660 ft. back of measuring drawbar. 40 cars: 16 empty, 24 loaded. Kind of cars: 29 box, 10 gondola, 1 caboose. Average weight per car = 40.44 tons.

1	2	3	4	5	6	7	8	9	10	11	12	13
Method	Item	Mile Post	Section Length	Pull P	Accel. A	Speed V_1	Speed V_2	Grade G	Direction	Velocity	Speed V	Resistance R
Point Columns 5, 6, and 9 to 13 show Momentary values	1	141.33		7800	0			— 1.50	+ 0°	4	27.20	5.39
	2	142.12		7900	0			— 1.83	+11° R	5	26.55	5.57
	3	144.65		7500	0			— 4.04	+ 0°	7	30.20	6.17
	4	145.56		6050	0			— 5.25	+ 0°	6	31.70	5.73
	5	147.33		4550	0			— 9.46	+ 0°	6	38.00	6.40
	6	153.18		5900	0			— 6.81	+65° R	6	29.46	6.23
	7	155.97		14900	0			+ 9.32	—60° R	8	16.55	5.68
	8	157.87		7250	0			+ 0.88	—45° R	6	15.18	4.15
	9	156.97		14100	0			+ 8.15	—60° R	11	17.77	5.62
	10	158.87		10400	0			+ 1.08	—60° R	14	20.95	6.02
Section Colums 5 and 9 to 13 show Average Values	1	139.00—140.21	6420	9100		23.14	25.72	— 3.91	+40° R	3	24.31	5.75
	2	140.21—141.56	7116	8200		25.72	27.50	— 4.82	+ 0°	4	26.95	5.97
	3	141.56—142.93	7188	7800		27.50	29.10	— 4.55	+10° R	5	27.23	5.67
	4	142.93—143.80	4616	7100		29.00	31.22	— 8.92	+ 0°	7	30.00	5.76
	5	143.80—145.16	7220	6950		31.22	31.20	— 4.17	+ 0°	7	30.78	5.89
	6	146.25—147.49	6560	4950		35.30	37.90	—15.13	+ 0°	6	37.30	6.79
	7	148.22—148.91	3632	4950		36.25	33.82	+ 1.67	+15° R	6	35.36	5.68
	8	150.79—151.78	5216	6950		30.20	29.10	— 0.40	+35° R	4	29.63	5.32
	9	151.78—152.57	4196	7400		29.10	28.55	+ 0.06	+60° R	5	28.60	5.08
	10	152.57—153.18	3176	7500		28.55	29.46	— 5.94	+65° R	6	28.87	5.74
	11	156.11—156.97	4552	14800		16.90	17.77	+ 8.15	—60° R	11	17.25	5.60
	12	157.48—158.25	4016	8850		17.23	17.23	+ 1.01	—45° R	6	16.11	5.09
	13	159.30—159.87	3032	13550		19.77	19.77	+ 5.48	—60° R	14	19.70	6.29
	14	160.80—161.79	5212	7750		26.64	26.64	— 5.68	—60° R	14	27.35	6.94
	15	162.59—163.28	3644	9200		22.90	24.37	— 4.35	—55° R	12	23.66	6.01
	16	164.96—165.66	3696	10550		20.37	21.73	— 0.16	—30° R	9	21.00	5.51
	17	166.19—166.84	3412	11800		20.55	18.60	+10.13	—25° R	8	19.40	5.01
	20	165.66—166.19	2828	10000		21.73	20.55	+ 5.45	—30° R	7	21.41	5.34
	21	159.87—160.62	3956	10400		19.77	25.55	—11.88	—60° R	13	22.46	6.34
	22	147.49—148.22	3860	4700		37.80	36.25	— 5.27	+10° R	7	37.60	6.96
	23	145.16—146.25	5716	6600		31.20	35.30	—13.76	+ 0°	6	32.50	5.99

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* For complete table heading see Table 36, p. 99.

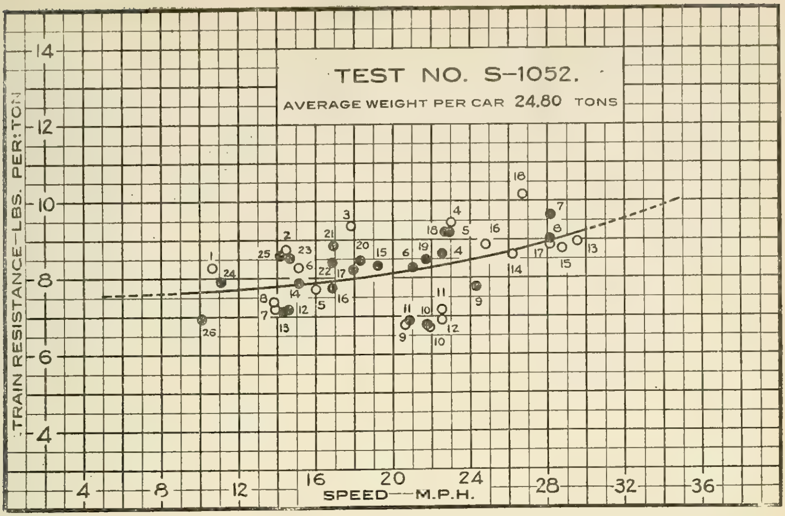
TEST NO. S-1052.
AVERAGE WEIGHT PER CAR 24.80 TONS
TRAIN RESISTANCE—LBS. PER TON
14
12
10
8
6
4
4
8
12
16
20
24
28
32
36
SPEED—M.P.H.

FIG. 39

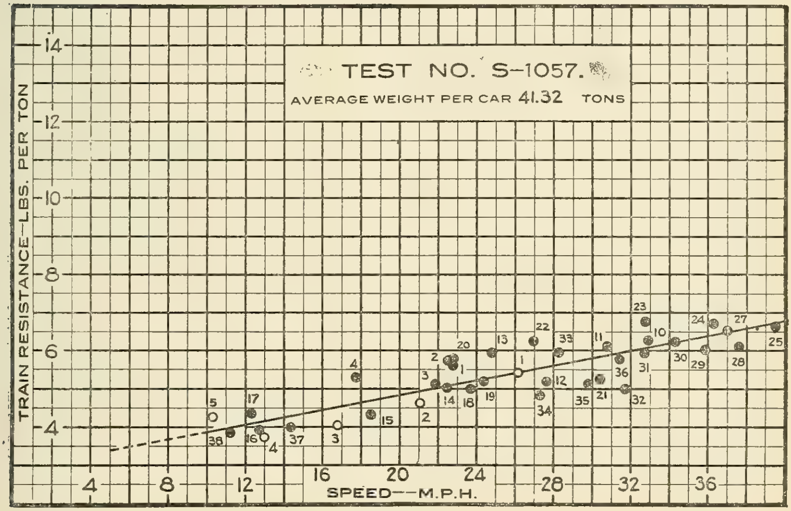
TEST NO. S-1057.
AVERAGE WEIGHT PER CAR 41.32 TONS
TRAIN RESISTANCE—LBS. PER TON
14
12
10
8
6
4
4
8
12
16
20
24
28
32
36
SPEED—M.P.H.

FIG. 40

TABLE 56 TEST NO. S-1052

From Champaign to Mattoon, January 28, 1909. Weather: Continuous rain. Temperature: 36° F. at start, 40° F. at end of test. Total weight behind measuring drawbar = 1514 tons, excluding the test car. Train length = 2430 ft. Center of mass 1316 ft. back of measuring drawbar. 61 cars: 44 empty, 17 loaded. Kind of cars: 36 box, 23 gondola, 1 flat, 1 caboose. Average weight per car = 24.80 tons.

1	2	3	4	5	6	7	8	9	10	11	12	13
Method of Calculation	Item No.	Location on Road Milepost No.	Length of Section feet	Total Drawbar Pull pounds	Acceleration Miles per hour per second	Speeds At Entrance to Section m. p. h.	Speeds At Exit from Section m. p. h.	Grade + Up − Down feet per mile	Wind Approximate Direction	Wind Approximate Velocity m. p. h.	Speed m. p. h.	Net Train Resistance pounds per ton
				P	*A*	*V*1	*V*2	*G*			*V*	*R*
Point Columns 5, 6, and 9 to 13 show Momentary Values	1	168.75		20850	0			+14.52	−45° L	14	10.64	8.27
	2	167.12		16050	0			+ 4.99	−50° L	19	14.45	8.71
	3	165.72		14400	0			+ 0.43	−60° L	18	17.32	9.35
	4	161.23		9550	0			− 8.25	−70° L	12	23.00	9.43
	5	159.84		13800	0			+ 3.75	−50° L	14	16.00	7.70
	6	157.37		16750	0			+ 7.38	−55° L	10	15.10	8.26
	7	155.97		16400	0			+ 9.66	−50° L	11	13.90	7.18
	8	155.11		15800	0			+ 8.10	−50° L	11	13.86	7,37
	9	152.52		9900	0			− 0.54	−80° L	6	20.64	6.75
	10	151.34		9750	0			− 0.65	90° L	7	21.90	6.69
	11	153.50		8650	0			− 3.77	−85° L	6	22.55	7.15
	12	149.60		9550	0			− 1.52	+70° L	6	22,46	6.89
	13	147.20		5800	0			−13.44	+85° L	10	29.47	8.92
	14	148.29		6900	−0.0388			− 0.74	+85° L	8	26.20	8.60
	15	147.44		5800	−0.0166			− 8.73	90° L	9	28.80	8,75
	16	148.57		9200	−0.0352			+ 1.71	+80° L	7	24.82	8.84
	17	146.59		8500	+0.0401			−18.85	+85° L	10	28.10	8.87
	18	146.33		8900	+0.0453			−22.88	+85° L	11	26.73	10.17

Section Columns 5, and 9 to 13 show Average Values	4	142.87—143.62	3972	9600		21.64	23.15	— 9.18	—80° L	10	22.55	8.61
	5	143.62—144.38	4032	8850		23.15	21.61	— 5.70	—65° L	13	22.92	9.19
	6	144.38—145.20	4312	10000		21.64	21.55	— 4.14	—66° L	10	21.00	8.24
	7	146.22—147.15	4956	8000		25.91	29.29	—18.46	+85° L	10	28.16	9.61
	8	147.15—148.29	5980	6200		29.29	26.20	— 7.56	90° L	9	28.13	9.00
	9	148.29—149.09	4268	8450		26.20	23.00	+ 1.17	+80° L	7	24.26	7.76
	10	151.12—151.85	3828	9400		22.10	21.28	— 0.28	90° L	7	21.74	6.77
	11	151.85—152.55	3676	9800		21.28	20.64	+ 0.32	—80° L	6	20.90	6.88
	12	156.01—156.74	3840	16850		14.10	15.00	+ 9.22	—54° L	11	14.54	7.16
	13	155.29—156.01	3780	16000		14.18	14.10	+ 9.22	—50° L	11	14.31	7.12
	14	156.74—157.37	3332	16100		15.00	15.10	+ 7.29	—55° L	10	15.15	7.82
	15	158.23—159.24	5344	11200		18.00	18.00	— 2.37	—55° L	12	19.20	8.30
	16	159.24—159.80	2964	13300		18.00	15.90	+ 7.31	—45° L	13	16.84	7.73
	17	159.80—160.69	4732	12500		15.90	21.36	— 7.92	—50° L	14	17.92	8.21
	18	160.69—161.45	3996	9600		21.36	22.82	—10.47	—70° L	12	22.70	9.16
	19	161.45—162.17	3816	9550		22.82	18.91	+ 2.31	—60° L	14	21.68	8.46
	20	162.17—163.08	4828	13400		18.91	19.50	+ 0.23	—55° L	13	18.29	8.44
	21	164.85—165.69	4460	15200		15.82	17.82	+ 0.35	—60° L	18	16.90	8.84
	22	165.69—166.67	5172	14600		17.82	15.18	+ 6.48	—60° L	16	16.80	8.39
	23	166.67—167.26	3116	16100		15.18	13.86	+ 7.88	—50° L	19	14.66	8.52
	24	168.57—169.13	2928	20400		10.91	12.64	+12.10	—45° L	14	11.09	7.90
	25	169.13—169.60	2492	17000		12.61	15.40	+ 1.25	—50° L	13	14.15	8.56
	26	171.44—171.72	1484	22600		12.32	8.50	+31.20	50° L	14	10.12	6.91

TABLE 57 Test No. S-1057

From Champaign to Gilman, March 6, 1909. Weather: Fair. Temperature: 34° F. at start, 40° F. at end of test. Total weight behind measuring drawbar = 2107 tons, including the test car. Train length = 1830 ft. Center of mass 860 ft. back of measuring drawbar. 51 cars: 8 empty, 43 loaded. Kind of cars: 23 box, 22 gondola, 3 flat, 1 tank, 1 test, 1 caboose. Average weight per car = 41.32 tons.

1	2	3	4	5	6	7	8	9	10	11	12	13
Method of Calculation	Item No.	Location on Road	Length of Section feet	Total Drawbar Pull pounds	Acceleration miles per hour per second	Speeds		Grade + Up − Down feet per mile	Wind		Speed m. p. h.	Net Train Resistance pounds per ton
		Milepost No.				At Entrance to Section m. p. h.	At Exit from Section m. p. h.		Approximate Direction	Approximate Velocity m. p. h.		
				P	*A*	*V*1	*V*2	*G*			*V*	*R*
Point Columns 5, 6, and 9 to 13 show Momentary Values	1	104.55		13600	−0.0561			+16.76	+10°L	8	26.16	5.41
	2	103.87		16800	−0.0723			+26.88	+ 5°L	13	21.02	4.63
	3	103.57		19550	−0.0638			+29.78	"	13	16 80	4.04
	4	103.29		24950	−0.0440			+32.38	"	13	13.00	3.73
	5	102.93		28350	0			+24.28	+10°L	6	10.32	4.26

Section Columns 5 and 9 to 13 show Average Values	1	117.94—117.18	4004	12800		22.57	23.05	+ 0.20	+20° R	6	22.75	5.62
	2	117.18—115.94	6596	13150		23.05	22.16	+ 2.41	+15° R	7	22.50	5.75
	3	115.91—115.36	3044	12950		22.16	21.42	+ 4.58	+20° R	6	21.85	5.14
	4	114.69—114.22	2472	17000		18.20	17.98	+ 7.90	+15° R	6	17.75	5.30
	10	106.08—105.53	2892	9150		32.35	32.08	— 4.02	+10° L	7	32.86	6.28
	11	105.53—105.02	2704	10050		32.08	29.20	+ 8.40	+10° L	8	30.74	6.11
	12	105.02—104.56	2428	11950		29.20	26.16	+13.92	+10° L	8	27.60	5.20
	13	104.56—104.25	1636	14600		26.16	24.10	+14.20	+10° L	8	24.79	5.93
	14	104.25—103.87	1976	15700		24.10	21.02	+19.24	+ 5° L	13	22.45	5.03
	15	103.87—103.57	1624	18350		21.02	16.80	+29.60	+ 5° L	13	18.45	4.32
	16	103.57—103.05	2704	24000		16.80	10.58	+31.25	+ 5° L	13	12.72	3.92
	17	103.05—102.40	3436	24000		10.58	18.88	+ 5.53	+10° L	6	12.33	4.37
	18	102.40—101.65	3988	12800		18.88	25.76	—11.25	+25° L	9	23.65	5.00
	19	101.65—101.24	2144	12800		25.76	23.50	+11.82	+25° L	9	24.38	5.20
	20	101.24— 99.79	7680	13500		23.50	28.72	— 4.88	+25° L	8	22.77	5.80
	21	99.79— 98.95	4452	6950		28.72	28.25	— 4.03	+25° L	8	30.38	5.25
	22	98.95— 98.05	4744	8100		28.25	30.32	—11.02	+20° L	9	26.95	6.26
	23	98.05— 97.50	2884	5800		30.32	34.54	—28.02	—35° L	11	32.76	6.78
	24	97.50— 96.05	7704	5400		34.70	37.55	—15.83	—35° L	11	36.24	6.71
	25	96.05— 95.38	3476	4950		37.55	41.10	—25.98	+35° L	12	39.50	6.64
	26	95.38— 94.60	4144	4450		41.10	37.90	— 1.02	+35° L	12	40.38	6.73
	27	94.60— 93.93	3528	6600		37.90	37.25	— 6.44	+35° L	12	37.00	6.53
	28	93.93— 93.31	3308	6100		37.25	37.25	— 8.46	+35° L	12	37.60	6.11
	29	90.09— 89.50	3156	5900		36.21	35.25	— 4.52	+35° L	11	35.86	6.02
	30	89.50— 88.92	3016	6900		35.25	33.55	— 0.70	+35° L	11	34.28	6.23
	31	88.92— 88.02	4792	7550		33.55	32.45	— 3.42	+35° L	11	32.68	5.93
	32	88.02— 86.79	3500	7600		32.45	30.62	— 0.41	+35° L	7	31.66	4.99
	33	86.79— 86.20	3108	8850		30.62	27.60	+ 5.78	+40° L	9	28.25	5.93
	34	86.20— 85.74	2396	9250		27.60	27.80	— 1.98	+40° L	9	27.23	4.82
	35	83.88— 83.38	2616	9800		29.21	30.02	— 4.64	+40° L	9	29.75	5.14
	36	83.38— 82.16	6444	8750		30.02	31.40	— 6.72	+40° L	9	31.40	5.79
	37	103.57—103.29	1472	22100		16.80	13.00	+31.20	+ 5° L	13	14.34	4.00
	38	103.29—103.05	1232	26400		13.00	10.58	+31.30	+ 5° L	13	11.20	3.88

TABLE 58 TEST NO.S-1061*

From Champaign to Gilman, March 13, 1909. Weather: Fair. Temperature: 41° F. at start, 38° F. at end of test. Total weight behind measuring drawbar = 2252 tons, including the test car. Train length = 1785 ft. Center of mass 850 ft. back of measuring drawbar. 44 cars: 3 empty, 41 loaded. Kind of cars: 37 Gondola, 5 flat, 1 test, 1 caboose. Average weight per car = 51.20 tons.

1	2	3	4	5	6	7	8	9	10	11	12	13
Method	Item	Mile Post	Section Length	Pull P	Accel. A	Speed V_1	Speed V_2	Grade G	Direction	Velocity	Speed V	Resistance R
Section Columns 5. and 9 to 13 show Average Values	1	117.14—115.91	6496	11550		18.20	16.41	+ 2.40	+70° L	5	17.05	4.87
	2	115.91—115.34	3000	12000		16.41	14.95	+ 5.02	+70° L	5	15.73	4.48
	3	111.66—110.96	3724	21900		18.13	10.25	+25.70	90° L	5	12.10	4.10
	4	110.96—109.84	5888	22400		10.25	17.05	+ 9.43	+75° L	10	11.47	4.21
	5	109.84—109.22	3304	14000		17.05	25.00	—17.44	—85° L	7	20.50	5.87
	6	109.22—108.31	4792	9850		25.00	23.00	— 0.33	+75° L	6	25.15	5.88
	7	106.86—106.12	3904	7850		29.81	32.20	—14.50	+70° L	7	31.30	6.38
	8	106.12—105.58	2872	7150		32.20	31.91	— 5.70	+70° L	7	32.65	5.79
	9	105.58—104.96	3304	9250		31.91	28.20	+ 7.90	+65° L	7	30.00	5.77
	10	104.96—104.26	3676	12100		28.20	22.57	+14.75	+85° L	7	25.05	5.13
	11	104.26—103.65	3224	17150		22.57	15.49	+21.90	+60° L	7	19.10	5.06
	12	103.65—103.31	1800	22450		15.49	9.70	+30.00	+80° L	9	12.27	4.15
	13	103.31—103.04	1464	27050		9.70	5.15	+31.00	+65° L	4	6.88	3.43
	14	103.31—103.18	720	26200		9.70	7.37	+32,30	+65° L	4	8.18	3.18
	15	103.18—103.04	744	28000		7.37	5.15	+29.90	+65° L	4	5.90	3.67
	16	98.14— 97.61	2776	7650		24.23	29.57	—27.40	+65° L	8	27.03	6.67
	17	97.61— 95.76	9800	6000		29.57	36.17	—18.75	+60° L	8	32.60	6.73
	18	95.76— 95.29	2472	4450		36.10	37.68	—23.50	+50° L	10	37.40	7.64
	19	95.29— 94.58	3772	4450		37.68	34.10	+ 2.03	+50° L	10	36.75	5.91
	20	94.58— 93.79	4136	5600		34.09	33.60	— 7.68	+45° L	10	33.16	5.95
	21	93.79— 93.24	2956	5200		33.60	32.91	— 7.15	+45° L	10	33.55	6.09
	22	86.71— 85.77	4960	11000		20.06	19.10	+ 1.28	90° L	9	19.00	4.91
	23	83.67— 82.97	3728	8250		22.70	24.03	— 6.00	+60° L	7	23.10	4.78
	25	81.65— 81.30	1868	8300		16.98	17.52	— 5.10	+80° L	8	16.97	4.93

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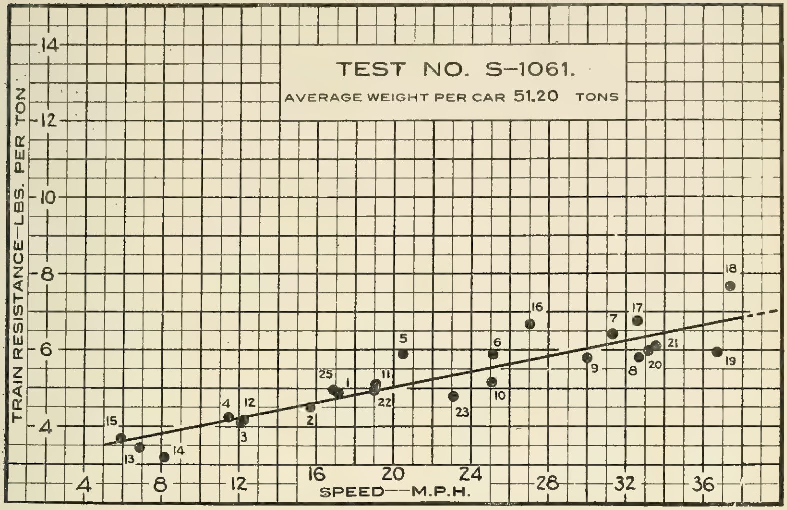
* For complete table heading see Table 36, p. 99.


TEST NO. S–1061.
AVERAGE WEIGHT PER CAR 51.20 TONS
TRAIN RESISTANCE—LBS. PER TON
SPEED—M.P.H.
4
6
8
10
12
14
4
8
12
16
20
24
28
32
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14
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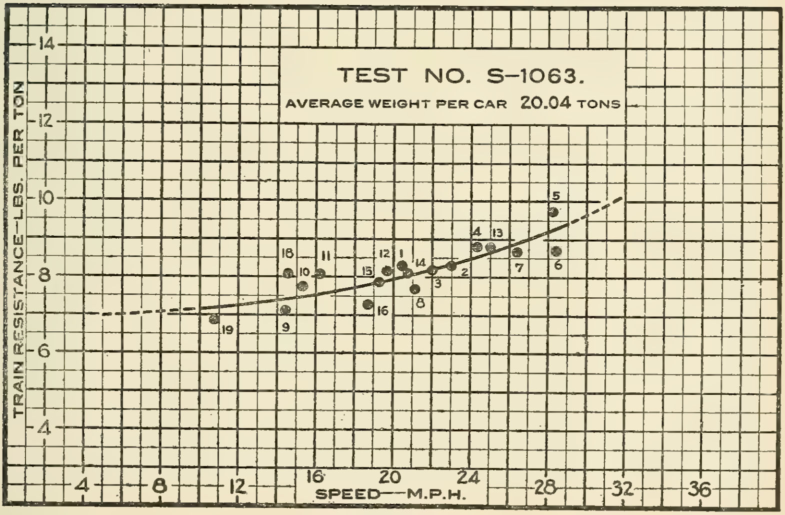
FIG. 41


TEST NO. S–1063.
AVERAGE WEIGHT PER CAR 20.04 TONS
TRAIN RESISTANCE—LBS. PER TON
SPEED—M.P.H.
4
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8
10
12
14
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12
16
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24
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FIG. 42

TABLE 59 TEST NO. S–1063*

From Champaign to Mattoon, March 19, 1909. Weather: Intermittent rain. Temperature: 39° F. at start, 40° F. at end of test. Total weight behind measuring drawbar = 1484 tons, excluding the test car. Train length = 3060 ft. Center of mass 1200 ft. back of measuring drawbar. 74 cars: 70 empty, 4 loaded. Kind of cars: 4 box, 69 gondola, 1 caboose. Average weight per car = 20.04 tons.

1	2	3	4	5	6	7	8	9	10	11	12	13
Method	Item	Mile Post	Section Length	Pull P	Accel. A	Speed V_1	Speed V_2	Grade G	Direction	Velocity	Speed V	Resistance R
Section Columns 5 and 9 to 13 show Average Values	1	141.71—142.84	6000	10800		20.74	21.61	− 3.74	+35° R	13	20.45	8.26
	2	143.53—144.45	4900	8450		22.91	22.10	− 5.40	+35° R	14	23.00	8.29
	3	144.45—145.34	4672	9800		22.10	22.71	− 5.20	+35° R	14	22.00	8.15
	4	145.34—146.42	5700	8850		22.71	27.21	−14.90	+40° R	15	24.30	8.77
	5	146.42—147.20	4144	6900		27.21	28.61	−16.95	+40° R	15	28.25	9.70
	6	147.20—147.83	3336	6700		28.61	28.00	− 9.01	+40° R	15	28.40	8.69
	7	147.83—148.60	4064	7200		28.00	24.91	− 2.34	+40° R	15	26.40	8.64
	8	152.50—153.52	5416	10100		20.35	22.14	− 4.90	+30° R	13	21.10	7.66
	9	155.78—156.82	5484	16050		14.30	15.10	+ 8.95	+20° R	10	14.40	7.10
	10	156.82—157.37	2912	16000		15.10	15.24	+ 7.80	+20° R	10	15.30	7.71
	11	157.37—158.16	4156	15600		15.24	17.73	+ 2.80	+30° R	10	16.20	8.03
	12	158.16—159.35	6336	12450		17.73	19.09	− 0.84	+30° R	10	19.65	8.14
	13	161.21—161.48	1472	9200		25.00	25.10	− 7.50	+30° R	13	25.00	8.79
	14	162.17—163.12	5028	12000		21.69	21.61	+ 0.10	+30° R	12	20.75	8.09
	15	165.07—165.77	3720	13200		18.11	19.61	− 0.14	+35° R	12	19.25	7.85
	16	165.77—166.85	5680	13050		19.60	16.56	+ 7.80	+35° R	12	18.70	7.24
	18	169.38—169.66	1492	14950		13.95	14.93	+ 1.77	+40° R	9	14.55	8.08
	19	171.55—171.71	870	22200		11.96	9.86	+31.50	+25° R	8	10.78	6.84

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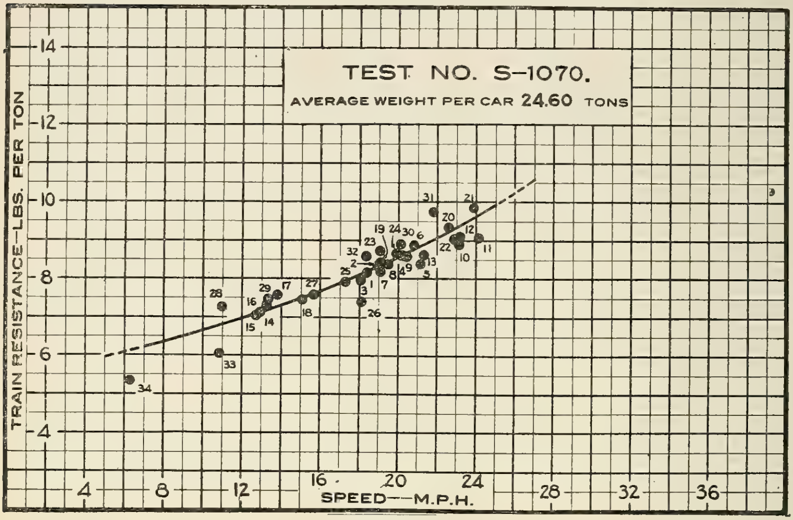
* For complete table heading see Table 36, p. 99.

TABLE 60 TEST NO. S-1070

From Champaign to Mattoon, April 17, 1909. Weather: Fair. Temperature: 58° F. at start, 71° F. at end of test. Total weight behind measuring drawbar = 1622 tons, including the test car. Train length = 2400 ft. Center of mass 1091 ft. back of measuring drawbar. 66 cars: 49 empty, 17 loaded. Kind of cars: 21 box, 28 gondola, 15 stock, 1 test, 1 caboose. Average weight per car = 24.60 tons.

1	2	3	4	5	6	7	8	9	10	11	12	13
Method	Item	Mile Post	Section Length	Pull P	Accel. A	Speed V_1	Speed V_2	Grade G	Direction	Velocity	Speed V	Resistance R
Section Columns 5 and 9 to 13 show Average Values	1	140.20—140.89	3636	11150		17.90	19.53	— 6.55	+ 0°	1	18.35	8.16
	2	140.89—141.70	4304	10800		19.53	18.65	— 2.94	+ 0°	1	18.90	8.31
	3	141.70—142.70	5308	11850		18.65	19.61	— 2.98	+ 0°	1	18.10	7.94
	4	142.70—143.38	3572	10150		19.61	21.19	— 9.47	+ 0°	1	20.25	8.57
	5	143.38—143.79	2164	9200		21.19	21.75	— 9.25	+ 0°	1	21.10	8.38
	6	143.79—144.37	3056	9150		21.75	20.13	— 4.33	+ 0°	1	20.80	8.86
	7	144.37—145.03	3496	10400		20.13	19.40	— 3.32	+ 0°	1	19.05	8.26
	8	145.03—145.38	1856	9900		19.40	19.98	— 8.26	+ 0°	1	19.45	8.36
	9	145.38—146.15	4040	9050		19.98	22.57	—13.00	+ 0°	1	20.40	8.57
	10	146.15—146.47	1692	5000		22.57	23.97	—22.50	+ 0°	1	23.10	8.88
	11	146.47—147.21	3892	5650		23.97	24.71	—16.40	+ 0°	1	24.10	9.04
	12	147.21—147.82	3236	5800		24.71	22.70	— 9.00	+ 0°	1	23.20	9.08
	13	147.82—148.32	2660	7700		22.70	20.61	— 3.77	+ 0°	1	21.30	8.60
	14	155.43—155.95	2740	16800		13.52	12.85	+ 9.80	+60° L	7	12.90	7.10
	15	155.94—156.41	2432	17500		12.85	13.10	+ 9.35	+60° L	7	12.75	7.06
	16	156.41—156.87	2424	17750		13.10	13.96	+ 7.83	+60° L	7	13.21	7.30
	17	156.87—157.36	2632	17600		13.96	14.30	+ 8.04	+60° L	7	13.80	7.54
	18	157.36—158.10	3864	16600		14.30	17.12	+ 3.14	+60° L	4	15.05	7.42
	19	158.10—159.29	6284	13950		17.12	18.87	— 1.35	+60° L	4	19.05	8.40
	20	160.55—160.80	1324	12650		21.90	23.63	—15.20	—75° L	3	22.60	9.32
	21	160.80—161.36	2980	11600		23.63	24.45	— 9.57	—75° L	3	23.90	9.84
	22	161.36—162.19	4368	11300		24.45	20.43	+ 2.30	—75° L	3	22.90	9.02
	23	162.19—162.77	3072	14100		20.43	19.53	+ 2.15	—75° L	3	19.02	8.70
	24	162.77—163.16	2040	13400		19.53	20.43	— 4.27	—75° L	3	19.90	8.63
	25	164.94—165.73	4188	14700		16.30	18.40	— 0.19	90° L	9	17.30	7.90
	26	165.73—166.16	2248	13600		18.40	17.74	+ 4.70	90° L	9	18.05	7.36
	27	166.16—166.85	3660	15050		17.74	14.62	+ 9.72	90° L	9	15.60	7.56
	28	168.36—168.69	1692	20750		11.40	10.98	+15.60	90° L	12	11.00	7.28
	29	168.69—169.63	4984	18650		10.98	16.45	+ 5.10	90° L	12	13.32	7.43
	30	169.63—170.56	4876	13600		16.45	22.70	—10.70	—65° L	6	20.10	8.87
	31	170.56—170.83	1440	12700		22.70	21.77	+ 0.37	—65° L	6	21.80	9.73
	32	170.83—171.42	3084	13550		21.77	14.30	+15.75	—65° L	6	18.30	8.58
	33	171.42—171.75	1752	20950		14.30	8.75	+31.90	+80° L	4	10.85	6.02
	34	171.86—172.10	1308	27050		7.60	6.00	+33.10	+80° L	4	6.38	5.32

or complete table heading see Table 36, p. 99.


TEST NO. S–1070.
AVERAGE WEIGHT PER CAR 24.60 TONS
TRAIN RESISTANCE–LBS. PER TON
14
12
10
8
6
4
SPEED—M.P.H.
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8
12
16
20
24
28
32
36
31
21
20
12
19
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30
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23
32
22
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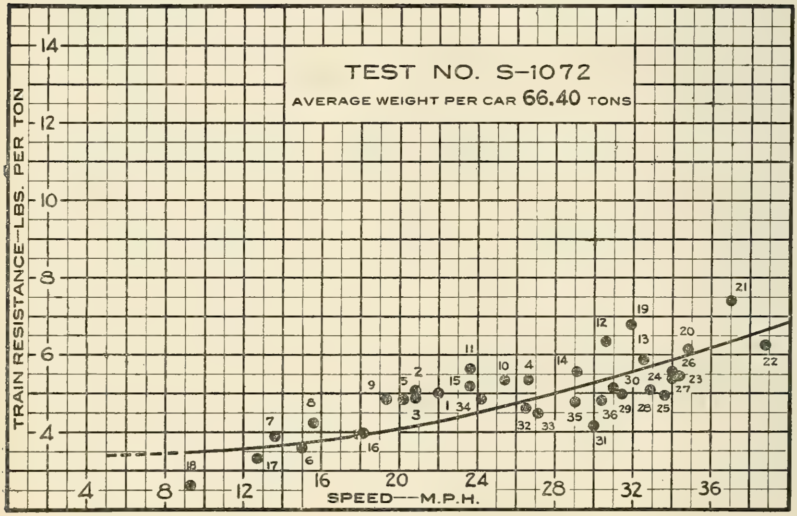
FIG. 43


TEST NO. S–1072
AVERAGE WEIGHT PER CAR 66.40 TONS
TRAIN RESISTANCE–LBS. PER TON
14
12
10
8
6
4
SPEED—M.P.H.
4
8
12
16
20
24
28
32
36
21
19
12
13
20
22
11
14
10
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26
5
2
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30
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23
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FIG. 44

TABLE 61 Test No. S-1072*

From Champaign to Gilman, May 1, 1909. Weather: Fair. Temperature: 35° F. at start, 37° F. at end of test. Total weight behind measuring drawbar = 1859 tons, excluding the test car. Train length = 1200 ft. Center of mass 600 ft. back of measuring drawbar. 28 cars: 1 empty, 27 loaded. Kind of cars: 27 gondola, 1 caboose. Average weight per car = 66.40 tons.

1	2	3	4	5	6	7	8	9	10	11	12	13
Method	Item	Mile Post	Section Length	Pull P	Accel. A	Speed $V1$	Speed $V2$	Grade G	Direction	Velocity	Speed V	Resistance R
Section Columns 5 and 9 to 13 show Average Values	1	118.31—117.62	3456	8600		22.30	21.82	+ 0.15	+75° L	22	22.00	4.98
	2	117.62—116.09	8212	10000		21.82	20.27	+ 2.25	+75° L	22	20.80	5.07
	3	116.09—115.37	3816	12350		20.27	20.75	+ 3.74	+75° L	22	20.80	4.88
	4	112.20—111.87	1752	11750		28.85	24.78	+25.00	90° L	21	26.60	5.34
	5	111.87—111.36	2668	14100		24.78	16.80	+29.70	90° L	21	20.20	4.83
	6	111.36—110.80	2968	17800		16.80	14.55	+20.11	+80° L	19	15.00	3.58
	7	110.80—110.35	2400	19000		14.55	14.55	+16.72	+80° L	19	13.60	3.88
	8	110.35—109.95	2164	10200		14.55	16.25	— 0.98	+80° L	19	15.60	4.21
	9	109.95—109.25	3686	8550		16.25	24.16	—16.19	90° L	19	19.34	4.82
	10	109.25—108.75	2608	7400		24.16	25.30	— 7.49	90° L	19	25.40	5.34
	11	108.75—108.36	2072	8300		25.30	22.30	+ 9.42	90° L	19	23.60	5.61
	12	107.10—106.29	4260	6200		28.74	31.48	—14.87	+85° L	20	30.60	6.33
	13	106.29—105.66	3336	5400		31.48	31.62	— 8.23	+85° L	20	32.50	5.85
	14	105.66—104.98	3624	6300		31.62	27.02	+ 7.72	+85° L	20	29.10	5.54
	15	104.98—104.42	2944	7700		27.02	20.95	+15.06	+80° L	14	23.60	5.18
	16	104.42—103.87	2912	11800		20.95	15.35	+18.85	+80° L	14	18.10	3.97
	17	103.87—103.45	2240	20700		15.35	11.24	+29.48	+80° L	14	12.70	3.30
	18	103.45—103.04	2184	24040		11.24	8.70	+31.42	+80° L	14	9.30	2.61
	19	98.05— 97.21	4448	5550		28.20	34.43	—25.77	+75° L	18	31.90	6.76
	20	97.21— 96.29	4856	4950		34.43	35.72	—11.31	+75° L	18	34.80	6.13
	21	96.29— 95.72	2984	3350		35.30	38.50	—29.03	+75° L	18	37.00	7.40
	22	95.72— 94.76	5120	1900		38.50	36.10	— 7.53	+70° L	17	38.80	6.26
	23	94.76— 93.95	4284	2900		36.10	34.30	— 4.93	+70° L	17	34.40	5.45
	24	93.95— 93.24	3736	2500		34.32	33.25	— 7.21	+70° L	17	34.00	5.39
	25	92 48— 91.88	3200	4950		32.70	34.26	—11.88	+75° L	17	33.60	4.93
	26	90.90— 90.29	3232	5050		34.02	34.32	— 8.66	+75° L	17	34.00	5.57
	27	90.29— 89.53	4020	4850		34.32	33.55	— 5.12	+75° L	17	34.30	5.44
	28	89.53— 88.99	2888	5300		33.55	32.29	— 0.73	+75° L	17	32.90	5.09
	29	88.99— 88.29	3684	5450		32.29	31.00	— 1.43	+85° L	13	31.40	4.98
	30	88 29— 87.65	3404	5100		31.00	30.37	— 4.19	+85° L	13	31.00	5.11
	31	87.65— 86.78	4612	5600		30.37	28.62	+ 1.03	+85° L	13	30.00	4.15
	32	86.78— 85.86	4848	7100		28.62	26.60	+ 2.07	+85° L	13	26.50	4.61
	33	85.86— 84.77	5760	8850		26.60	25.23	+ 2.93	90° L	10	27.10	4.49
	34	84.77— 84.36	2136	12500		25.23	25.93	+ 1.98	90° L	10	24.20	4.84
	35	84.36— 83.55	4272	7400		25.93	30.13	—11.98	90° L	10	29.00	4.76
	36	83.55— 83.05	2672	6400		30.13	30.80	— 6.32	90° L	10	30.40	4.80

For complete table heading see Table 36, p. 99.

TABLE 62 TEST NO. S-1073*

From Champaign to Gilman. May 4, 1909. Weather: Fair. Temperature: 53° F. at start, 63° F. at end of test. Total weight behind measuring draw-bar = 1880 tons excluding the test car. Train length = 1200 ft. Center of mass 600 ft. back of measuring draw-bar. 28 cars: 1 empty, 27 loaded. Kind of cars: 27 gondola, 1 caboose. Average weight per car = 67.16 tons.

1	2	3	4	5	6	7	8	9	10	11	12	13
Method	Item	Mile Post	Section Length	Pull P	Accel. A_1	Speed V_1	Speed V_2	Grade G	Direction	Velocity	Speed V	Resistance R
Section Columns 5 and 9 to 13 show Average Values	1	115.97—115.36	3232	10700		29.80	29.10	+ 5.06	+40° R	12	29.40	4.64
	2	114.71—114.21	2648	11000		26.85	25.70	+ 8.18	+50° R	11	25.80	4.31
	3	113.13—112.53	3176	9100		28.65	32.90	−15.60	+45° R	14	30.80	5.13
	4	112.53—111.82	3752	7500		32.90	28.86	+12.52	+45° R	14	32.00	3.78
	5	111.82—111.43	2056	10300		28.86	23.12	+30.60	+45° R	14	25.50	3.79
	6	111.43 —111.03	2108	14150		23.12	19.40	+23.30	+55° R	8	20.50	3.82
	7	111.03—110.57	2396	15800		19.39	17.11	+19.80	+55° R	8	18.15	3.27
	8	110.57—109.94	3352	16000		17.11	21.32	+ 3.31	+55° R	8	18.50	3.97
	9	109.94—109.21	3888	11250		21.33	30.13	−16.82	+50° R	12	25.30	4.40
	10	109.21—108.30	4776	8650		30.13	29.68	+ 1.99	+50° R	12	31.00	4.23
	11	107.85—107.44	2160	8350		31.33	34.04	−14.90	+50° R	12	32.70	4.49
	12	106.68—106.08	3188	8200		37.70	40.10	−13.74	+50° R	19	39.50	5.57
	13	106.08—105.45	3292	7250		40.10	39.50	− 1.60	+50° R	19	40.80	5.46
	14	105.45—104.62	4436	7350		39.50	34.62	+11.50	+50° R	19	37.80	5.11
	15	104.62—103.81	4264	8500		35.90	29.20	+18.94	+55° R	14	32.30	4.33
	16	103.81—103.27	2856	10650		29.20	20.60	+ 3.09	+55° R	14	24.30	4.19
	17	96.30— 95.69	3212	2600		37.05	41.25	−28.90	+40° R	17	39.80	5.32
	19	94.74— 94.31	2304	3000		39.65	37.90	+ 2.75	+35° R	12	39.30	4.57
	20	90.56— 89.99	3012	800		10.34	12.76	− 9.80	+70° R	6	11.42	2.87
	21	89.99 — 89.48	2688	750		12.76	9.85	− 1.77	+70° R	6	11.46	2.74
	22	89.48— 88.74	3900	3350		9.85	8.57	− 1.62	+50° R	2	8.32	2.80
	23	88.74— 88.08	3520	4500		8.57	11.15	− 3.45	+ 0°	3	8.01	2.70
	24	87.35— 86.95	2124	1850		10.63	9.70	− 3.73	+25° L	3	11.15	3.00
	25	86.95— 86.32	3308	12200		9.70	10.33	+ 8.54	+ 0°	0	7.65	2.99
	26	86.32— 85.78	2876	11600		10.33	16.04	− 1.74	+ 0°	3	13.07	3.26
	27	85.78— 85.20	3060	8400		16.04	19.96	− 5.87	+15° R	7	18.17	3.53
	28	85.20— 84.75	2416	11200		19.96	16.48	+16.40	+ 5° R	5	18.20	3.32
	29	84.75— 84.30	2372	15500		16.48	21.34	− 3.12	+ 5° R	5	17.20	4.14
	30	84.30— 83.75	2896	10600		21.34	27.34	−12.95	+15° R	7	24.70	3.66
	31	83.75— 83.13	3284	9500		27.30	29.70	− 5.62	+45° R	10	28.00	4.33
	32	83.13— 82.66	2480	8800		29.70	32.45	−12.13	+15° R	12	30.70	4.58
	33	90.94— 90.56	2036	4000		7.05	10.35	− 6.48	+70° R	6	7.71	2.66
	34	97.22— 96.30	4892	3450		35.90	37.05	− 11.34	+20° R	12	37.10	4.96
	35	97.80— 97.22	3060	3800		31.75	35.90	−24.15	+35° R	14	34.80	4.90

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* For complete table heading see Table 36 p. 99.

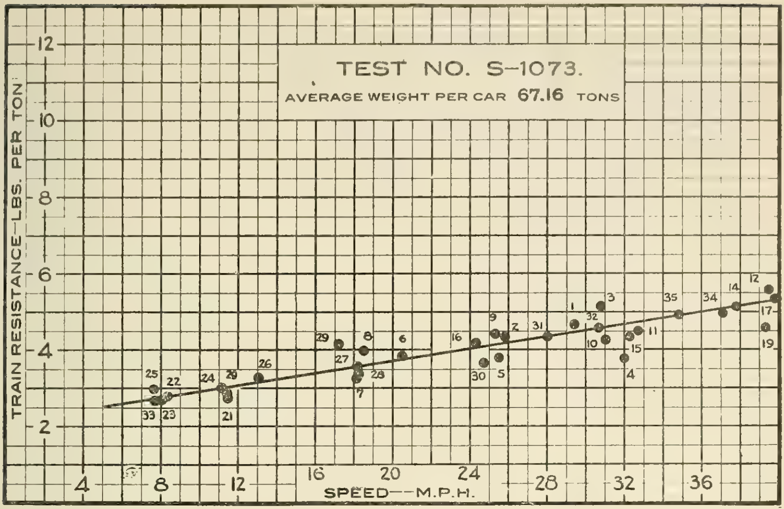
TEST NO. S–1073.
AVERAGE WEIGHT PER CAR 67.16 TONS
TRAIN RESISTANCE–LBS. PER TON
SPEED––M.P.H.
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Fig. 45

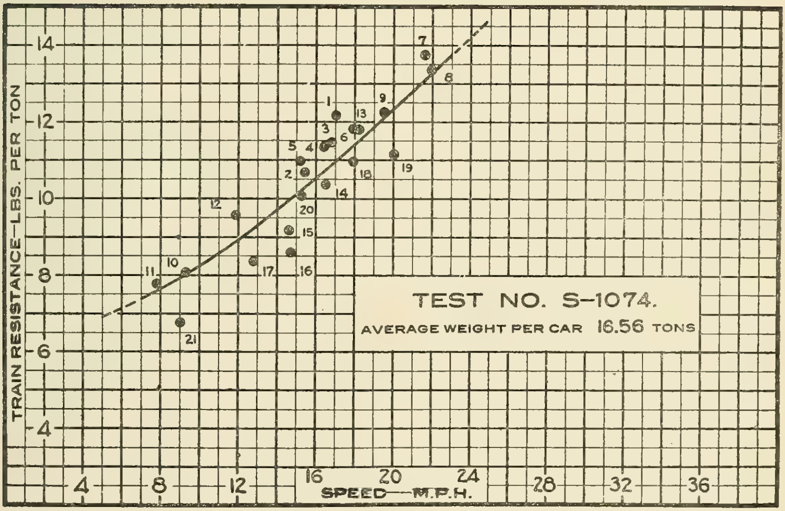
TEST NO. S–1074.
AVERAGE WEIGHT PER CAR 16.56 TONS
TRAIN RESISTANCE–LBS. PER TON
SPEED––M.P.H.
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Fig. 46

TABLE 63 TEST NO. S-1074*

From Champaign to Mattoon, May 7, 1909. Weather: Fair. Temperature: 45° F. at start, 60° F. at end of test. Total weight behind measuring drawbar = 1340 tons, including the test car. Train length = 3180 ft. Center of mass 1600 ft. back of measuring drawbar. 81 cars: 81 empty, 0 loaded. Kind of cars: 79 gondolas, 1 test, 1 caboose. Average weight per car = 16.56 tons.

1	2	3	4	5	6	7	8	9	10	11	12	13
Method	Item	Mile Post	Section Length	Pull P	Accel, A	Speed V_1	Speed V_2	Grade G	Direction	Velocity	Speed V	Resistance R
Section Columns 5 and 9 to 13 Show Average Values	1	140.88—141.71	4380	13400		17.43	16.35	− 4.10	−80° L	11	17.00	12.16
	2	141.71—142.84	6025	12950		16.35	16.50	− 2.88	−80° L	11	15.40	10.69
	3	142.84—143.77	4930	11000		16.50	17.12	− 9.43	−80° L	11	16.80	11.47
	4	143.77—144.73	3490	11050		17.12	15.46	− 5.41	−85° L	12	16.40	11.34
	5	144.43—145.35	4825	13200		15.46	16.72	− 4.60	−85° L	12	15.20	10.98
	6	145.35—146.21	4600	12600		16.72	20.18	−11 71	−85° L	12	17.90	11.81
	7	146.21—147.02	4280	10550		20.18	22.35	−19.62	−80° L	10	21.60	13.74
	8	147.02—147.81	4170	11350		22.35	21.54	−10.64	−80° L	10	21.90	13.37
	9	147.81—148.74	4895	12050		21.54	17.82	− 2.81	−80° L	10	19.50	12.25
	10	151.75—152.07	1640	7500		10.90	7.82	+ 0.32	90° L	12	9.30	8.04
	11	152.46—152.86	2076	10000		8.13	8.13	− 0.76	−85° L	9	7.80	7.75
	12	153.50—153.88	2010	10450		12.50	11.40	− 2.10	−85° L	13	11.90	9.56
	13	160.63—161.44	4305	10650		17.43	18.28	−11.53	90° L	10	18.20	11.80
	14	161.44—162.20	4016	11300		18.28	14.30	+ 1.18	90° L	10	16.50	10.35
	15	165.08—165.76	3658	14000		13.25	15.55	− 0.14	+65° L	9	14.60	9.18
	16	165.76—166.50	3100	13050		15.55	13.50	+ 5.96	+65° L	9	14.70	8.60
	17	166.50—166.91	2164	15000		13.50	12.68	+ 9.52	+65° L	9	12.84	8.33
	18	169.66—170.41	3936	13500		15.48	20.43	−11.00	+75° L	7	17.90	10.96
	19	170.41—170.82	2200	11250		20.43	19.45	− 3.84	+75° L	7	20.00	11.15
	20	170.82—171.60	4136	15100		19.46	11.07	+15.20	+75° L	7	15.23	10.04
	21	171.60—172.02	2256	23050		11.07	7.91	+32.78	+75° L	7	9.09	6.75

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*For complete table heading see Table 36, p. 99.

TABLE 64 Test No. S-1076*

From Champaign to Gilman, May 11, 1909. Weather: Fair. Temperature 51° F. at start, 67° F. at end of test. Total weight behind measuring drawbar–1818 tons, excluding the test car. Train length–1120 ft. Center of mass 500 ft. back of measuring drawbar. 26 cars: 1 empty, 25 loaded. Kind of cars: 25 gondola 1 caboose. Average weight per car–69.92 tons.

1	2	3	4	5	6	7	8	9	10	11	12	13
Method	Item	Mile Post	Section Length	Pull P	Accel. A	Speed $V1$	Speed $V2$	Grade G	Direction	Velocity	Speed V	Resistance R
Section Columns 5 and 9 to 13 Show Average Values	1	117.91—117.15	3976	8450		28.52	28.80	+ 0.40	+ 55° R	19	28.60	4.23
	2	117.15—116.10	5588	8700		28.80	27.82	+ 3.02	+ 55° R	19	28.20	4.32
	3	116.10—115.38	3820	8900		27.82	27.10	+ 3.87	+ 55° R	19	27.40	4.13
	4	114.77—114.28	2620	11000		24.78	23.70	+ 7.86	+ 60° R	18	23.80	4.44
	5	113.24—112.56	3590	8900		25.95	31.60	—15.60	+ 55° R	21	28.90	4.63
	6	112.56—112.04	2795	7550		31.60	30.02	+ 5.48	+ 55° R	21	31.80	4.45
	7	112.04—111.16	4710	11050		30.02	18.27	+27.70	+ 60° R	17	22.90	3.79
	8	111.16—110.64	2670	14250		18.27	15.09	+18.60	+ 65° R	13	16.50	3.50
	9	110.64—110.34	1575	16000		15.09	15.25	+13.40	+ 65° R	13	14.30	3.51
	10	110.34—109.94	2130	13650		15.25	19.25	— 0.99	+ 65° R	13	17.10	3.49
	11	119.94—109.56	2015	11650		19.25	24.12	—12.83	+ 60° R	17	21.10	4.13
	12	109.56—109.20	1940	9000		24.12	28.75	—21.76	+ 60° R	17	26.40	4.60
	13	109.20—108.30	4700	7950		28.75	27.92	+ 2.70	+ 60° R	17	29.20	4.03
	14	106.93—106.26	3550	7700		35.26	38.38	—14.55	+ 75° R	16	37.10	5.35
	15	106.26—105.34	4855	6250		38.38	37.40	— 2.61	+ 75° R	16	39.00	5.47
	16	105.34—104.25	5780	7050		37.40	30.45	+12.96	+ 75° R	16	34.40	4.53
	17	104.25—103.65	3180	8200		30.98	23.57	+25.08	+ 75° R	16	27.10	3.69
	18	103.65—103.16	2580	12250		23.57	14.80	+30.90	+ 75° R	16	18.50	3.93
	19	98.06— 97.43	3340	2200		30.20	34.75	—26.70	+ 60° R	28	32.50	5.28
	20	97.43— 96.79	3404	1300		34.75	35.75	—14.40	+ 60° R	28	35.60	4.77
	21	90.42— 89.63	4204	650		24.65	23.12	— 6.28	+ 50° R	16	23.90	3.93
	22	87.62— 87.40	1180	7250		4.13	6.93	— 2.24	+ 45° R	5	4.73	3.05
	23	87.40— 86.94	2405	2150		6.93	5.73	— 3.07	+ 45° R	5	8.42	2.77
	24	86.46— 85.84	3288	4950		7.53	8.90	— 1.60	+ 40° R	6	7.88	2.86
	25	85.84— 85.21	3344	2700		8.90	10.33	— 5.53	+ 40° R	6	10.36	3.02
	26	83.88— 83.09	4170	7800		23.00	25.03	— 5.82	+ 60° R	21	23.70	4.90
	27	83.09— 82.40	3652	6100		25.03	27.21	— 9.11	+ 60° R	21	26.20	4.69

*For complete table heading see Table 36, p. 99.

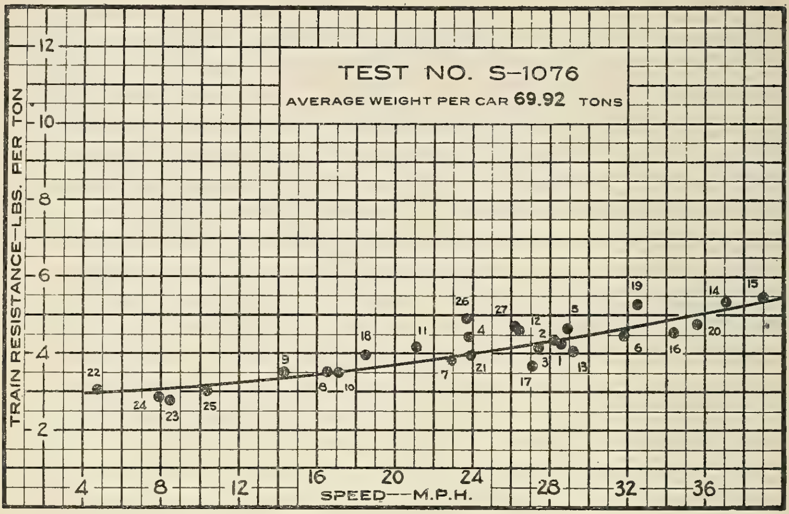
TEST NO. S–1076
AVERAGE WEIGHT PER CAR 69.92 TONS
TRAIN RESISTANCE—LBS. PER TON
SPEED—M.P.H.
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FIG. 47

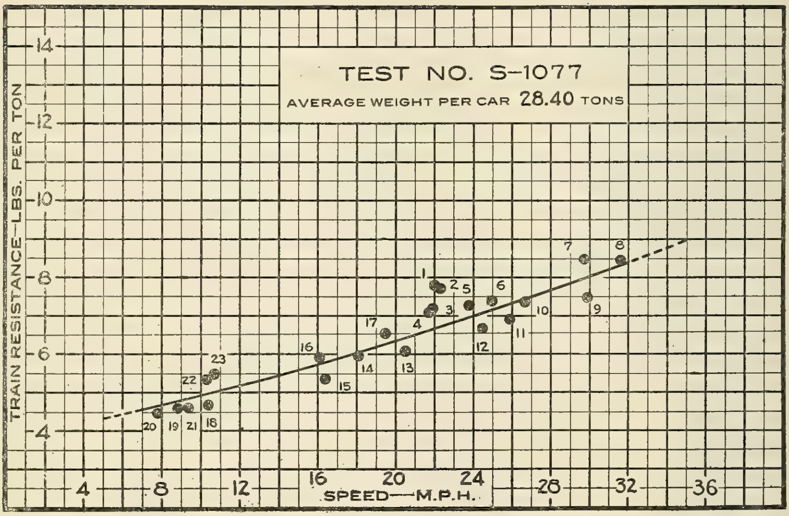
TEST NO. S–1077
AVERAGE WEIGHT PER CAR 28.40 TONS
TRAIN RESISTANCE—LBS. PER TON
SPEED—M.P.H.
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FIG. 48

TABLE 65 TEST NO. S-1077*

From Champaign to Mattoon, May 14, 1909. Weather: Fair. Temperature: 64° F. at start, 70° F. at end of test. Total weight behind measuring drawbar = 1505 tons, including the test car. Train length = 2145 ft. Center of mass 930 ft. back of measuring drawbar. 53 cars: 35 empty, 18 loaded. Kind of cars: 37 box, 14 gondola, 1 test, 1 caboose. Average weight per car = 28.40 tons.

1	2	3	4	5	6	7	8	9	10	11	12	13
Method	Item	Mile Post	Section Length	Pull P	Accel. A	Speed $V1$	Speed $V2$	Grade G	Direction	Velocity	Speed V	Resistance R
Section Columns 5 and 9 to 13 show Average Values	1	139.56—140.29	3885	8900		22.56	22.18	— 4.10	—65° R	14	22.00	7.77
	2	140.29—141.04	3930	8650		22.18	23.05	— 7.00	—65° R	14	22.30	7.70
	3	141.04—142.03	5785	9000		23.05	21.33	— 0.70	—65° R	14	21.90	7.18
	4	142.13—142.85	3820	8850		21.33	23.20	— 7.20	—65° R	13	21.70	7.08
	5	142.85—143.65	4195	8050		23.20	25.15	— 9.20	—65° R	13	23.80	7.26
	6	143.65—144.07	2200	7700		25.15	25.40	— 7.00	—65° R	13	25.00	7.37
	7	146.08—147.07	5235	7000		27.31	31.55	—18.90	—75° R	19	29.75	8.47
	8	147.07—148.03	5555	7350		31.55	31.20	— 8.60	—75° R	19	31.60	8.42
	9	148.13—148.62	2630	7350		31.20	29.27	+ 1.40	—75° R	19	29.90	7.47
	10	149.09—149.53	2350	8350		27.76	26.72	— 0.20	—75° R	13	26.70	7.33
	11	150.11—150.98	4565	8100		27.09	25.35	— 0.30	—75° R	13	25.90	6.90
	12	150.98—151.79	4310	8750		25.35	25.45	— 0.30	—75° R	13	24.50	6.65
	13	154.82—155.50	3620	10300		22.45	19.70	+ 7.90	—55° R	12	20.50	6.09
	14	155.50—156.11	3190	11400		19.70	17.25	+ 9.60	—55° R	12	18.10	5.94
	15	156.11—156.65	2900	12450		17.25	16.42	+ 9.50	—55° R	12	16.40	5.35
	16	156.65—157.79	2840	12650		16.42	16.19	+ 7.10	—55° R	12	16.10	5.90
	17	158.01—158.66	3440	11000		18.27	21.52	— 4.90	—65° R	12	19.50	6.53
	18	164.89—165.17	1484	6950		10.90	10.18	—15.20	—30° R	8	10.40	4.66
	19	165.17—165.63	2456	4950		10.18	7.98	— 0.40	—30° R	8	8.80	4.59
	20	165.63—166.01	2036	7600		7.98	7.22	— 2.60	—30° R	8	7.80	4.46
	21	166.21—166.53	1664	15000		8.57	10.17	+10.80	—25° R	10	9.40	4.60
	22	166.53—166.87	1812	13500		10.17	10.33	+ 9.30	—25° R	10	10.30	5.31
	23	166.87—167.23	1876	12650		10.33	11.55	+ 5.10	—25° R	10	10.70	5.48

*For complete table heading see Table 36, p. 99.

TABLE 66 TEST NO. S–1079*

From Champaign to Gilman, May 18, 1909. Weather: Fair. Temperature: 65° F. at start, 68° F. at end of test. Total weight behind measuring drawbar = 1685 tons, excluding the test car. Train length = 2070 ft. Center of mass 1015 ft. back of measuring drawbar. 51 cars: 14 empty, 37 loaded. Kind of cars: 45 box, 5 gondola, 1 caboose Average weight per car = 33.04 tons.

1 Method	2 Item	3 Mile Post	4 Section Length	5 Pull *P*	6 Accel. *A*	7 Speed V_1	8 Speed V_2	9 Grade *G*	10 Direction	11 Velocity	12 Speed *V*	13 Resistance *R*
Section Columns 5 and 9 to 13 show Average Values	1	118.04—117.31	3850	10050		22.44	22.04	+ 0.14	+85° R	20	21.80	6.23
	2	117.31—115.99	7035	9700		22.04	19.24	+ 2.56	+85° R	20	20.00	5.93
	3	115.99—115.34	3440	12500		19.24	19.96	+ 3.60	+85° R	20	19.50	5.48
	4	112.92—112.48	2305	10550		25.00	28.27	—14.90	+70° R	21	26.20	6.63
	5	112.48—111.82	3490	8950		28.27	23.62	+ 9.40	+70° R	21	26.50	6.57
	6	111.82—111.37	2380	14200		23.62	16.10	+29.70	+70° R	21	19.10	5.94
	7	111.37—110.79	3070	18550		16.10	13.45	+21.80	+70° R	21	13.50	4.51
	8	110.79—110.16	3310	19750		13.45	15.63	+14.00	+80° R	19	13.25	5.07
	9	110.16—109.83	1760	15000		15.63	18.65	— 1.70	+80° R	19	17.15	5.45
	10	109.83—109.21	3310	9500		18.65	24.92	—16.90	+80° R	19	21.50	6.29
	11	109.21—108.30	4800	6450		24.92	22.30	— 1.00	+80° R	19	24.20	6.01
	12	106.81—106.20	3250	7040		28.98	30.73	—14.30	+80° R	20	29.60	7.36
	13	106.20—105.56	3375	5150		30.73	30.10	— 7.50	+80° R	20	30.70	6.70
	14	105.56—104.96	3180	7750		30.10	25.82	+ 7.80	+80° R	20	27.20	6.89
	15	104.96—104.44	2740	11750		25.82	22.20	+14.60	+80° R	20	23.40	5.85
	16	104.44—103.87	3050	13500		22.20	17.98	+16.80	+65° R	15	19.80	5.52
	17	103.87—103.48	2053	17900		17.98	12.94	+28.00	+65° R	15	14.75	5.31
	18	103.48—103.06	2240	22250		12.94	9.54	+32,10	+65° R	15	10.55	3.40
	19	102.29—101.55	3905	11650		22.10	26.60	— 8.50	+75° R	23	25.40	6.21
	20	101.55—100.48	5685	12650		26.60	22.70	+10.30	+75° R	23	23.50	5.97
	21	100.48— 99.73	3980	12400		22.70	31.34	—19.50	+75° R	23	25.90	6.56
	22	99.73— 98.87	4530	9350		31.34	31.53	— 2.60	+65° R	23	32.60	6.36
	23	98.87— 98.00	4614	11050		31.53	35.70	—12.60	+65° R	23	31.50	7.09
	24	98.00— 97.31	3616	8650		35.60	40.45	—26.30	+65° R	23	37.90	8.00
	25	94.59— 93.65	4970	2700		34.60	32.90	— 7.40	+65° R	16	32.30	6.02
	26	88.97— 88.11	4506	4850		10.10	10.10	— 2.30	—85° R	9	9.17	3.75
	27	88.11— 87.22	4748	3700		10.10	10.10	— 3.30	—85° R	9	9.80	3.45
	28	87.22— 86.76	2428	3100		10.10	5.00	+ 2.60	—85° R	9	8.70	3.06
	29	86.32— 85.81	2645	6450		6.00	8.42	— 1.40	90° R	8	6.95	3.44
	30	84.17— 83.39	4150	10550		20.12	25.95	— 9.70	+75° R	16	23.50	5.42
	31	83.39— 82.46	4920	8600		25.95	28.75	— 9.20	+75° R	16	26.90	6.42

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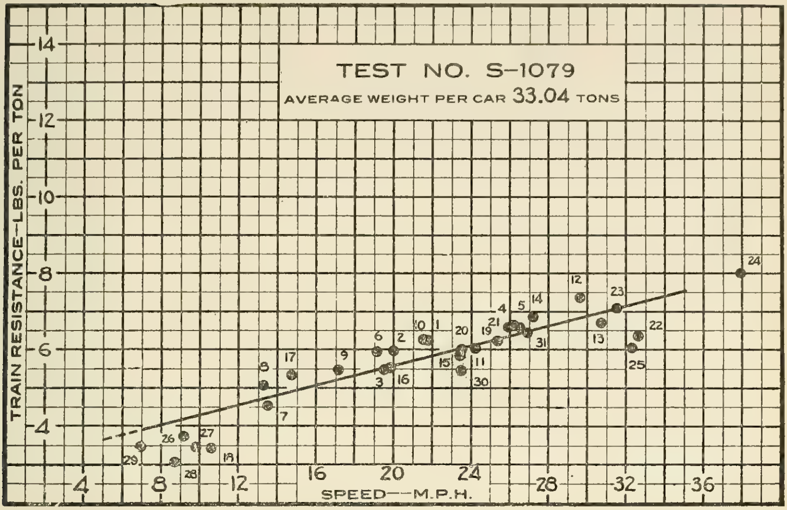
*For complete table heading see Table 36, p. 99.


TEST NO. S–1079
AVERAGE WEIGHT PER CAR 33.04 TONS
TRAIN RESISTANCE—LBS. PER TON
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SPEED—M.P.H.
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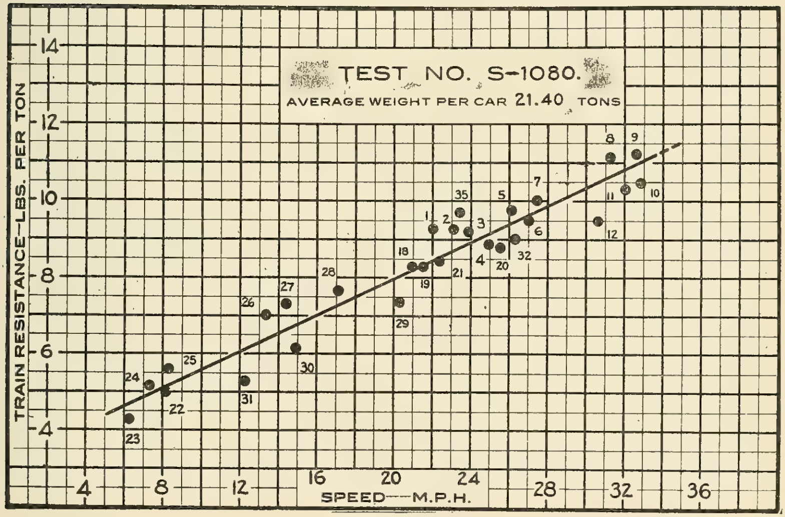
FIG. 49


TEST NO. S–1080.
AVERAGE WEIGHT PER CAR 21.40 TONS
TRAIN RESISTANCE—LBS. PER TON
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SPEED—M.P.H.
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FIG. 50

TABLE 67 TEST NO. S-1080*

From Champaign to Mattoon, May 21, 1909. Weather: Fair. Temperature: 50° F. at start, 70° F. at end of test. Total weight behind measuring drawbar = 1347 tons, including the test car. Train length = 2550 ft. Center of mass 920 ft. back of measuring drawbar. 63 cars: 57 empty, 6 loaded. Kind of cars: 8 box, 53 gondola, 1 test, 1 caboose. Average weight per car = 21.40 tons.

1	2	3	4	5	6	7	8	9	10	11	12	13
Method	Item	Mile Post	Section Length	Pull P	Accel. A	Speed V^1	Speed V^2	Grade G	Direction	Velocity	Speed V	Resistance R
Section Columns 5 and 9 to 13 show Average Values	1	139.61—140.34	3872	11150		22.02	22.70	— 4.09	+30° L	12	22.00	9.27
	2	140.34—140.92	3044	11100		22.70	24.23	— 7.12	+30° L	12	23.07	9.25
	3	140.92—141 71	4192	10700		24.23	23.82	— 2.39	+30° L	12	23.82	9.20
	4	142.67—143.09	2196	10700		24.50	26.10	— 9.38	+25° L	11	24.95	8.86
	5	143.09—143.52	2300	10500		26.10	27.08	— 9.42	+25° L	11	26.14	9.75
	6	143.52—144.42	4752	10050		27.08	26.97	— 5.11	+25° L	11	27.00	9.49
	7	145.29—146.21	4828	10100		26.97	30.13	—13.67	+25° L	11	27.42	10.00
	8	146.21—146.73	2748	9850		30.13	32.35	—19.61	+25° L	11	31.23	11.13
	9	146.73—147.27	2868	9400		32,35	33.25	15.10	+25° L	11	32.60	11.22
	10	147.27—147.81	2888	9450		33.25	33.03	— 8.23	+ 0°	12	32.81	10.49
	11	147.81—148.35	2820	9650		33.03	31.90	— 3 37	+13° L	10	32.05	10.31
	12	148.35—148.73	2020	10300		31.90	30.62	+ 2.61	+13° L	10	30.60	9.50
	18	159.23—159.58	1844	12250		21.90	20.75	+ 7.16	+45° L	11	20.96	8.29
	19	159.58—160.56	5200	12100		20.75	25.16	- 5.48	+45° L	11	21.50	8.28
	20	161.33—162.18	4500	9100		27.22	23.56	+ 2.46	+40° L	11	25.56	8.79
	21	162.18—163.25	5244	10800		23.56	23.42	— 0.81	+40° L	11	22.35	8.42
	22	164.97—165.65	3580	6050		8 82	7.22	0.00	+15° L	12	8.14	5.00
	23	165.81—166.23	2212	9000		6.12	5 82	+ 6.68	+15° L	12	6.28	4.27
	24	166.41—166.90	2584	11850		7.52	7.52	+ 9.61	+15° L	12	7.34	5.16
	25	166.90—167.31	2192	10750		7.52	9.20	+ 3.85	+15° L	12	8.30	5.60
	26	168.26—168.71	2348	16850		13.95	13.28	+15.97	+20° L	12	13.34	7.01
	27	168.71—169.29	3060	16050		13.28	16.50	+ 6.21	+20° L	12	14.40	7.30
	28	169.29—169.60	1628	13650		16.50	17.90	+ 0.97	+20° L	12	17.08	7.64
	29	170.83—171.48	3424	12100		23.55	17.20	+18.65	+15° L	11	20.30	7.33
	30	171.48—171.75	1420	17600		17.20	13.70	+32.72	+15° L	11	14.90	6.12
	31	171.75—171.95	1080	20000		13.70	11.80	+33.74	+15° L	11	12.27	5.28
	32	160.56—161.33	4044	9100		25.16	27.22	—10.96	+40° L	11	26.27	9.00
	35	142.28—142.67	2060	12000		23.28	24.50	— 7.44	+25° L	11	23.41	9.71

* For complete table heading see Table 36, p. 99.

APPENDIX 6

APPENDIX 6

EXACT COORDINATES FOR THE CURVES OF FIG. 10 AND 11.

The original drawings from which Fig. 10 and 11 have been reproduced were drawn to a scale about twice as great as that of the cuts shown in the report. From these original drawings, the values of the coordinates of the various curves of both figures have been determined as accurately as possible; and these values are presented in Tables 68 and 69.

The curves of Fig. 10 (and of Fig. 3 to 9) may be accurately reproduced by the use of Table 68; the curves of Fig. 11 may be reproduced from the values given in Table 69. The tables are presented merely to permit the accurate reproduction, to any scale, of the curves of the report; they are not intended for use in determining values of resistance. For the latter purpose Table 3 is more convenient and sufficiently accurate.

TABLE 68

VALUES OF RESISTANCE FOR TRAINS OF VARIOUS AVERAGE CAR WEIGHTS AND FOR DIFFERENT SPEEDS

This table presents the co-ordinates of the original curves from which Figures 3 to 9 and Figure 10 were reproduced.

Average Weight Per Car tons		Train Resistance—Pounds Per Ton							Average Weight Per Car tons	
		Column Headings Indicate the Various Speeds								
		5 m. p. h	10 m. p. h.	15 m. p. h.	20 m. p. h.	25 m. p. h.	30 m. p. h.	35 m. p. h.		
15		7.62	8.20	8.81	9.56	10.37	11.24	12.25		15
	16	7.44	8.00	8.61	9.34	10.13	10.98	11.95	16	
	18	7.10	7.63	8.22	8.92	9.68	10.47	11.39	18	
	20	6.77	7.30	7.85	8.53	9.26	10.00	10.89	20	
	22	6.45	6.97	7.49	8.16	8.84	9.56	10.41	22	
	24	6.16	6.64	7.14	7.79	8.46	9.16	9.94	24	
25		6.02	6.50	6.98	7.62	8.28	8.95	9.72		25
	26	5.88	6.35	6.81	7.44	8.10	8.77	9.52	26	
	28	5.61	6.07	6.51	7.11	7.76	8.40	9.12	28	
	30	5.38	5.80	6.23	6.80	7.43	8.05	8.75	30	
	32	5.13	5.54	5.98	6.51	7.12	7.72	8.40	32	
	34	4.92	5.31	5.72	6.24	6.82	7.40	8.06	34	
35		4.82	5.20	5.61	6.11	6.68	7.26	7.91		35
	36	4.72	5.10	5.50	5.99	6.55	7.11	7.77	36	
	38	4.55	4.90	5.28	5.74	6.29	6.83	7.48	38	
	40	4.38	4.70	5.06	5.50	6.03	6.57	7.20	40	
	42	4.22	4.52	4.88	5.29	5.80	6.32	6.95	42	
	44	4.08	4.38	4.70	5.09	5.59	6.10	6.71	44	
45		4.01	4.30	4.61	4.99	5.49	6.00	6.60		45
	46	3.95	4.21	4.52	4.90	5.38	5.90	6.49	46	
	48	3.82	4.08	4.38	4.71	5.20	5.71	6.28	48	
	50	3.72	3.96	4.24	4.56	5.03	5.52	6.10	50	
	52	3.61	3.85	4.11	4.42	4.88	5.36	5.91	52	
	54	3.52	3.75	3.99	4.30	4.74	5.20	5.74	54	
55		3.48	3.71	3.94	4.25	4.68	5.12	5.67		55
	56	3.43	3.67	3.90	4.20	4.62	5.05	5.60	56	
	58	3.37	3.58	3.81	4.10	4.50	4.93	5.47	58	
	60	3.30	3.50	3.73	4.02	4.42	4.83	5.36	60	
	62	3.23	3.44	3.67	3.97	4.34	4.74	5.27	62	
	64	3.18	3.39	3.60	3.90	4.29	4.68	5.18	64	
65		3.15	3.36	3.58	3.88	4.25	4.64	5.14		65
	66	3.12	3.32	3.55	3.85	4.22	4.61	5.11	66	
	68	3.09	3.30	3.50	3.80	4.18	4.57	5.06	68	
	70	3.05	3.26	3.47	3.76	4.13	4.52	5.01	70	
	72	3.02	3.22	3.44	3.73	4.10	4.49	4.98	72	
	74	3.01	3.19	3.42	3.71	4.08	4.48	4.93	74	
75		3.00	3.18	3.41	3.70	4.07	4.47	4.91		75

TABLE 69

Values of Resistance at Various Speeds and for Trains of Different Average Weights Per Car

This table presents the co-ordinates of the original curves from which Fig. 11 is reproduced

Speed miles per hour	Train Resistance—Pounds Per Ton													Speed miles per hour
	Column Headings Indicate the Average Weights Per Car													
	15 tons	**20** tons	**25** tons	**30** tons	**35** tons	**40** tons	**45** tons	**50** tons	**55** tons	**60** tons	**65** tons	**70** tons	**75** tons	
5	7.62	6.77	6.02	5.38	4.82	4.39	4,01	3.72	3.49	3.30	3,16	3.05	3.00	5
6	7.73	6.86	6.12	5.46	4.90	4.43	4.07	3.77	3.52	3.33	3.19	3,08	3.03	6
7	7.83	6.97	6.21	5.53	4.98	4,50	4.12	3.81	3.56	3.37	3.23	3.12	3.07	7
8	7.96	7.06	6.31	5.62	5.04	4.57	4.18	3.86	3,60	3.40	3.26	3.16	3.10	8
9	8.07	7.18	6.40	5.71	5.11	4.62	4.22	3.90	3.64	3.44	3.30	3.20	3.13	9
10	8.19	7.29	6.50	5.80	5,20	4.69	4.28	3.96	3.69	3.49	3.34	3.24	3.18	10
11	8.30	7.40	6.60	5.90	5.29	4.76	4.33	4.00	3.73	3.52	3.38	3.29	3.21	I1
12	8.42	7.51	6.71	5.98	5.37	4.83	4.40	4.04	3.78	3.58	3.42	3.33	3.26	12
13	8.56	7.63	6.81	6.08	5.46	4.90	4.47	4.11	3.83	3.62	3.47	3.38	3.31	13
14	8.70	7.76	6.92	6.18	5.53	4.98	4.53	4.18	3.89	3.68	3.52	3.43	3.36	14
15	8.82	7.88	7.01	6.28	5.64	5.06	4.60	4.24	3.94	3.73	3.57	3.48	3,41	15
16	8.98	8.00	7.12	6.39	5.73	5.13	4.68	4.31	4.00	3.80	3.62	3.53	3.47	16
17	9.10	8.13	7.24	6.49	5.82	5.23	4.75	4.38	4.05	3.86	3.68	3,60	3.52	17
18	9.25	8.27	7.37	6.60	5.92	5.32	4.83	4.45	4.12	3.92	3.74	3.66	3.58	18
19	9.40	8.40	7.49	6,71	6.01	5.41	4.91	4.52	4.19	3.98	3.81	3.72	3.64	19
20	9.56	8.53	7.60	6.82	6.11	5.50	5.00	4.60	4,27	4.04	3.88	3.79	3.71	20
21	9.71	8.69	7.72	6.93	6.22	5.60	5.08	4.69	4.32	4.11	3.94	3.85	3.78	21
22	9.88	8.82	7.86	7.03	6.33	5.70	5.17	4.78	4.41	4.18	4.00	3.92	3.84	22
23	10.02	8.97	7.99	7.14	6.44	5.80	5,27	4.86	4.49	4.25	4.07	3.99	3.92	23
24	10.20	9.11	8.11	7.27	6.55	5.90	5.37	4.94	4.58	4.33	4.15	4.06	3.98	24
25	10.37	9.26	8.25	7.40	6.67	6.01	5.46	5.03	4.66	4.41	4.23	4.13	4.04	25
26	10.52	9.42	8.38	7.52	6,79	6.11	5.57	5.12	4.75	4.50	4.31	4.21	4.12	26
27	10.71	9.57	8.51	7.65	6.91	6.21	5.67	5.22	4.83	4.58	4.40	4.29	4.20	27
28	10.89	9.72	8.67	7.78	7.01	6.33	5.78	5.32	4.92	4.67	4.48	4.38	4.29	28
29	11.06	9.89	8.81	7.91	7.12	6.45	5.88	5.43	5.01	4.76	4,57	4.46	4.36	29
30	11.25	10.03	8.96	8.04	7.26	6.58	5.99	5.53	5.11	4.86	4.66	4.53	4.45	30
31	11.43	10.20	9.10	8.18	7.39	6.71	6 10	5.64	5.21	4.95	4.75	4.63	4.53	31
32	11.63	10.37	9.26	8.31	7.51	6.83	6.21	5.76	5.32	5.04	4.85	4.73	4.62	32
33	11.84	10.53	9.41	8.46	7.63	6.96	6.33	5,87	5.43	5.15	4.95	4.83	4.72	33
34	12.04	10.71	9.57	8.60	7.78	7.08	6.47	5.99	5.54	5.26	5.05	4.92	4.82	34
35	12.25	10.89	9.72	8.75	7.91	7.20	6.60	6.10	5.67	5.36	5.16	5.01	4.92	35
36	12.47	11.07	9.89	8.90	8.04	7.35	6.73	6.23	5.78	5.48	5.27	5.12	5.01	36
37	12.69	11.23	10.04	9.04	8.19	7.49	6.87	6.36	5,90	5.59	5.38	5.22	5.12	37
38	12.91	11.42	10.21	9.20	8.33	7.64	7.00	6.49	6.02	5.71	5.48	5.33	5.22	38
39	13.12	11.61	10.39	9.36	8.48	7.79	7.13	6.63	6.15	5.83	5.60	5.44	5.33	39
40	13.35	11.80	10.55	9.51	8.62	7.93	7.29	6.78	6.28	5.95	5.72	5.55	5.45	40

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AN INVESTIGATION OF BUILT-UP COLUMNS UNDER LOAD

BY

ARTHUR N. TALBOT

AND

HERBERT F. MOORE

UNIVERSITY OF ILLINOIS
ENGINEERING EXPERIMENT STATION

URBANA, ILLINOIS
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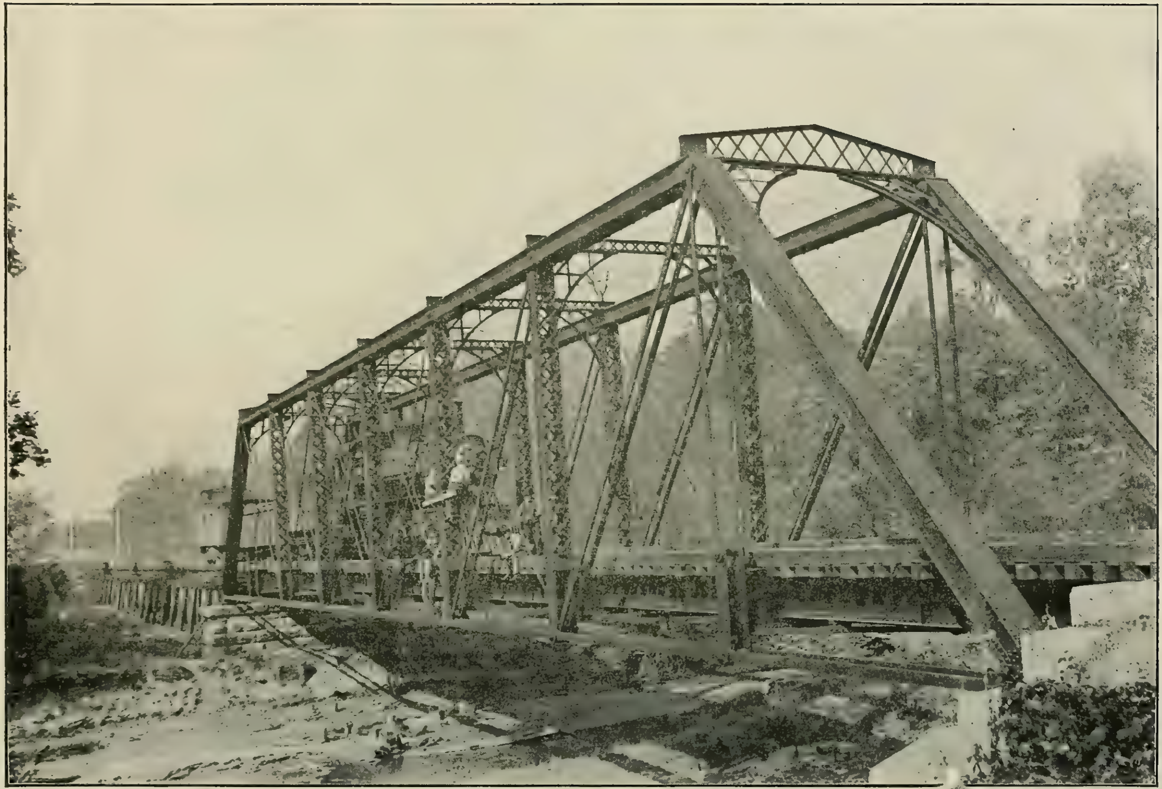

White Heath Bridge and Test Train

UNIVERSITY OF ILLINOIS
ENGINEERING EXPERIMENT STATION

BULLETIN NO. 44 JUNE, 1910

AN INVESTIGATION OF BUILT-UP COLUMNS UNDER LOAD

BY ARTHUR N. TALBOT, PROFESSOR OF MUNICIPAL AND SANITARY ENGINEERING AND IN CHARGE OF THEORETICAL AND APPLIED MECHANICS, AND HERBERT F. MOORE, ASSISTANT PROFESSOR IN THEORETICAL AND APPLIED MECHANICS

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AN INVESTIGATION OF BUILT-UP COLUMNS UNDER LOAD

I. INTRODUCTION.

1. *Scope of Bulletin.*—The investigation described in this bulletin was taken up with a view of determining experimentally: (1) something of the way in which the compressive stresses in built-up columns vary over the cross-section of the channels or other component parts and throughout their length; (2) something of the amount and distribution of stress in the lattice bars of columns, and also the action of similar bars under separate tests with similar conditions of fastening and eccentricity; and (3) the general relation which exists between the component parts and the column as a whole. The investigation may be said to differ from the usual tests of columns, where the main purpose is to determine the ultimate strength of the column and the effect of length, in that emphasis is placed on measuring the distribution and range of stress over the various parts of the column. The making of tests to determine the distribution of stress in such compression pieces has commonly been held to be impracticable. In several respects these tests may be said to be pioneer tests along the line of the determination of the distribution of stress under load, whether that load be applied by a testing machine or by a locomotive and train in service.

The principal tests were made on the following compression pieces: (a) a steel column (called Column No. 1) built up of angles, plates, and lattice bars, all the parts being light with respect to the size of the column; (b) four wrought-iron bridge posts which had seen long service in a bridge truss; and (c) three posts and a top chord in a railroad bridge under service. The tests of (a) and (b) were made in a testing machine; for (c) a locomotive and cars formed the load. The auxiliary tests which were made on lattice bars and other parts have an important bearing in connection with the design of columns.

It is well known that built-up compression pieces (whether long or short) are not perfect, the natural imperfections of the component parts being increased in the process of fabrication. To non-homogeneity of structure and lack of straightness in the component angle or channel are added such further imperfections as kinks and eccentric connection of parts, which go to increase the opportunities for local flexure in the component parts and for flexural stresses in the column as a whole. An attempt has been made in these tests to measure the deformations in the presence of such conditions, and to find the general distribution of stress. In view of the many limitations surrounding such tests, the results are to be taken as suggestive and qualitative, and not as exact determinations.

The methods of testing and the results of the tests are given under the heads: II. Laboratory Tests of Columns, III. Field Tests of Columns, and IV. Tests of Lattice Bars, Small Columns, and Column Material. Under V. Discussion, is given a general discussion of the tests and a short discussion of the bearing of the results upon methods of design, together with a summary of the conclusions.

2. *Acknowledgment.*—The steel test column was furnished by the American Bridge Co., Mr. August Ziesing, President. The wrought-iron columns were bridge posts taken from an old bridge of the Chicago, Burlington and Quincy Railroad, and were furnished through the courtesy of Mr. L. J. Hotchkiss, Assistant Bridge Engineer. The arrangement for the test of the railroad bridge was made through Mr. R. E. Gaut, Bridge Engineer of the Illinois Central Railroad, and to him and to Mr. C. R. Westcott, Division Superintendent of the Illinois Central Railroad, special acknowledgment is made for the use of the engine, train, and crew for eight days.

The investigation was the work of the Engineering Experiment Station of the University of Illinois. The observations both in the laboratory tests and the field tests were made by skilled observers, and care was taken to make the tests trustworthy in all respects. Much of the experimental work has been described in Vol. LXV of the Transactions of the American Society of Civil Engineers.

3. *Basis of Column Formulas.*—For the purposes of this discussion a column may be considered to be a prismatic piece, having a length several times its breadth, and subject to nominal axial compression. It is, then, a compression piece in which there is chance for failure at one side of the column by reason of the added stresses of lateral flexure. The column may be a

single solid piece throughout, as in the case of a rolled section, or it may be built up of rolled angles or channels by riveting the members together or by connecting them by plates or lattice bars, as is the usual practice in bridges and other structural steel work.

The analysis ordinarily used in deriving column formulas assumes the existence of flexure in the column as a whole. The deflection in the axis of the column may result from initial eccentricity at the point of application of the load, lack of homogeneity in the material (which will allow bending to begin), a general bend in the column as a whole, or a combination of two or more of these conditions. Except for the initial eccentricity, the amount of the bending moment producing flexural stress is usually assumed to vary as the square of $\frac{l}{r}$ (ratio of length to least radius of gyration). The constants for these semi-rational formulas have usually been obtained by fitting the formulas to the experimental results, and the results of tests have also been used as a basis of purely empirical formulas. Unfortunately, the range of experiments for any given form or type of column has not been large, and especially has information been lacking on the properties of short compression pieces of the character used in the larger columns. In the light of recent tests it seems probable that too much weight has been given to the bending action of the column as a whole and also that, for short and medium lengths, the strength of the column at its elastic limit is not as great, relatively, as it has been considered to be.

Column analysis further assumes the integrity of cross-section of the column; that is, it assumes that the component angles or channels will act as a unit to resist bending so that a plane section before loading will remain plane after loading. It may well be questioned whether the ordinary riveted column does maintain its integrity to such an extent that the whole section will act as a unit. In the case of lightly built columns and of those having parts inadequately laced together, it would seem that the looseness or lack of integrity may greatly affect the distribution of stresses. At any rate, this is a subject which should be investigated before accepting integrity of section as a feature of column action. It will be seen that if the component members or parts of a section act somewhat independently, the conditions of column action will not agree with the usual assumptions. If, for example, the individual parts of a column are very thin, there may be a tendency for these thin parts to wrinkle under compression, and failure by such wrinkling may occur at loads less than would cause the column to fail by direct compression or by bending as a whole. Professor Lilly, of Trinity College, Dublin, has made an experimental study of this wrinkling effect in small columns of various cross-sections.*

Again, it may be noted that in the process of fabrication of the built-up columns, kinks and bends are formed in the component pieces. This condition produces initial stresses and also gives local bending action under load in these pieces. It will be shown that a very slight bend in a thin channel member may cause very severe stresses to be set up. During the process of fitting and riveting in column fabrication the material may be stressed locally beyond the yield point. It would seem reasonable to suppose that a column may have a much different distribution of stress throughout its members than would be expected in an ideal column which would be perfectly straight and homogeneous and which would have its integrity of cross-section preserved under load.

4. *Secondary Stresses in Columns.*—Such conditions as eccentricity of loading, crookedness of column, either general or local, and lack of homogeneity of parts, which act to produce variations in longitudinal stresses throughout the length in the different members of a column, produce transverse shear in the column. To resist this the column parts are riveted together or connected by plates and lattice bars. These shearing forces are usually small, but in the larger columns they become very important. Various attempts have been made to investigate mathematically the distribution and amount of shear in the different parts of a column, but all such analyses depend upon integrity of cross-section and assume a regular change in bending moment from end to middle of column. The conditions attending fabrication of built-up columns seem to make it impracticable to assert with any degree of certainty how far these assumptions may be right. Besides, it is possible that, by reason of conditions

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*The Strength of Columns, Proceedings of the Institution of Mechanical Engineers, June, 1905. The Design of Struts, Engineering (London), January 10, 1908.

resulting from the process of erection, torsional stresses may be set up in the column, and the ordinary column is very poorly adapted to resist such stresses. It seems very desirable that experiments on columns should include a measurement of the stresses in the lattice members.

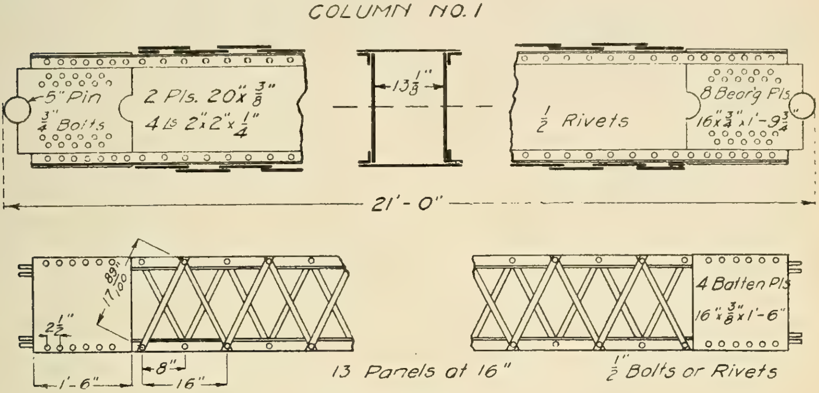

FIG. 1. STEEL TEST COLUMN NO. 1.

5. *Methods of Experimental Study.*—Much of the column testing described in engineering literature has had for its main subject the determination of the ultimate strength of the columns. Observations have been made on the shortening of the column as a whole, and the elastic limit or yield point of the column has been determined. Generally speaking, however, there has been no study of the distribution of deformations throughout the test piece. In outlining the tests described in this bulletin it was believed that a study of the distribution of stress over the cross-section and throughout the length of the column would give results which would be of value. The method adopted was, therefore, to make a measurement of the deformations produced over short spaces at different parts of the column under test and to make these measurements so that the lateral bending of the component pieces of the column could be found. The tests also included the measurement of the deformations in lacing bars and their distribution over the bar. To throw light upon the action of the column, special tests were also made on lacing bars.

II. Laboratory Tests of Columns.

6. *Description of Columns.*—One steel column and four wrought-iron columns were tested. The steel column (designated here as Column No. 1) was specially designed for the purpose of these tests, and was of a much less stocky section than are the built-up columns ordinarily used in bridge and building construction. Fig. 1 shows the details of this column. The section of this column was chosen because it seemed to offer better opportunities than a less flimsy column for the study of distribution of stress, lateral and longitudinal, under the conditions of the test, and also because the stresses developed in the latticing could better be studied. It was thought that the variations of stress due to methods of fabrication, handling in shipment, and conditions of applying the load would be more pronounced than in a

TABLE 1.

Data of Columns.

Column Designation	Column No. 1	Wrought-iron Posts		White Heath Bridge	
		No. 2, 3, 4 and 5	Retest 2a and 4a	Posts U_3L_3 North U_3L_3 South	Upper Chord U_3U_4 South
Area of column section, inches	18.76	17.64	17.64	12.02	48.67
Length, c. to c.	21 ft.	15 ft. 10 in.	14 ft. 7 in.	25 ft.	19 ft. 10 in.
End conditions	Pin parallel to lacing	Pin parallel to lacing	Pin parallel to lacing	Lower end pin, upper end riveted	Riveted
$\frac{l}{r}$ axis parallel to lacing,	37.8	43.5	40.1	66.1	40.7
$\frac{l}{r}$ axis perpendicular to lacing	37.2	41.2	38.0	41.0	29.6
$\frac{l}{r}$ of each flange member, axis perpendicular to lacing for full length column	593	400	367	416	——
$\frac{l}{r}$ of each flange member, axis as before, for distance between adjacent lacing rivets	37.7	33.7	33.7	22.2	——
Lattice bars, dimension of section, inches	1x¼-in. and 1¼x$\frac{7}{16}$-in.	2½x⅜-in.	2½x⅜-in.	2¼x⅜-in.	2¾x⅜-in. on bottom
Kind of lacing	Single	Double	Double	Double; riveted at crossing	One cover plate
Angle of lattice bar with axis of column	63° 30′	45°	45°	45°	45° on bottom

stocky column, and hence that the flimsy column would be capable of more accurate study. In this connection it should be noted, however, that the chord members of large bridges are sometimes built up of parts relatively as thin as the parts of this test column. The steel column was built at the Lassig plant of the American Bridge Company. In the earlier tests of this column the lattice bars were fastened in place by turned bolts in reamed holes, and two sizes of lattice bars were used in the different tests, but in the later tests the bars were riveted in place.

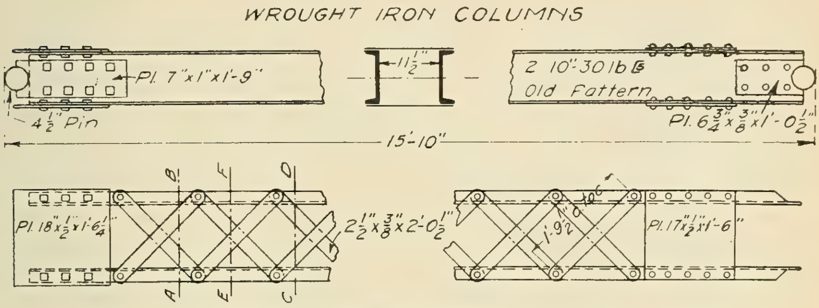

FIG. 2. WROUGHT-IRON TEST COLUMNS NO. 2, 3, 4 AND 5.

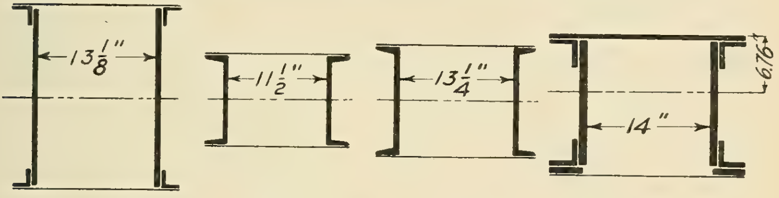

FIG. 3. CROSS-SECTIONS OF TEST COLUMNS.

The wrought-iron columns were from an old bridge of the Chicago, Burlington and Quincy Railroad. For the purpose of the test the posts were cut in two; the old ends were left as used in the bridge, and bearing plates and batten plates were bolted to the other ends. The proportions of these wrought-iron columns represented good practice at the time of the erection of the bridge. The columns became available for testing through the replacement of the bridge by a heavier structure; they were apparently in good condition. Fig. 2 shows the details of one of these columns. Fig. 3 shows to scale the cross-sections of all columns, both in the laboratory and in the field tests. Table 1 gives the general data of all columns tested.

7. *Testing Machine.*—The machine used in testing the columns was the Riehle vertical 600 000-lb. screw-power machine in the Laboratory of Applied Mechanics of the University of Illinois. This machine has a clear space of 36 in. between screws. There is thus room around a column for instrumental work. It will take compression specimens 25 ft. long. It is equipped with a heavy guide frame—not touching any part of the weighing apparatus—which takes any side thrust present in the test. The speed of head in nearly all tests was 0.4 in. per min. The machine has been shown to be accurate and trustworthy.

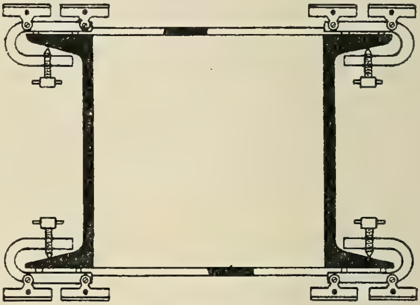

FIG. 4. ATTACHMENT OF EXTENSOMETER TO CHANNEL MEMBERS OF COLUMN.

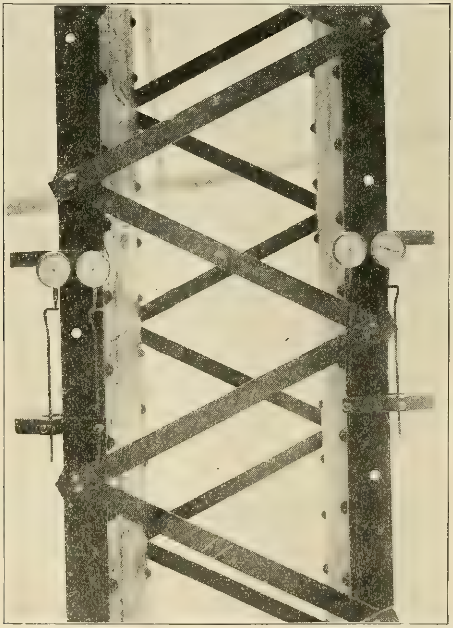

FIG. 5. EXTENSOMETERS IN PLACE ON CHANNEL MEMBERS OF COLUMN.

8. *Extensometers.*—In the earlier testing work various types of extensometers were tried. As a result of the trial the extensometers used in the later tests for measuring deformation in the

channel members consisted of Ames test gauges mounted on suitable frames. Each frame was in the shape of a C-clamp and bore against the channel member through three blunt points and a screw. Fig. 4 shows the shape of these clamps. These instruments magnify change of length by means of clockwork operating a hand rotating over a dial. They read directly to $\frac{1}{1000}$ in. and by estimation to $\frac{1}{10000}$ in. For measuring the deformation of the lattice bars of Column No. 1, a Ewing extensometer was used. In this instrument the displacement of a cross hair is viewed through a microscope. The instrument reads directly to $\frac{1}{5000}$ in., and by estimation to $\frac{1}{50000}$ in. It is a very accurate piece of apparatus but is not adapted to a wide range of size of specimens. It could not be used on the lattice bars of the wrought-iron columns, and on these bars the Ames test gauges were used.

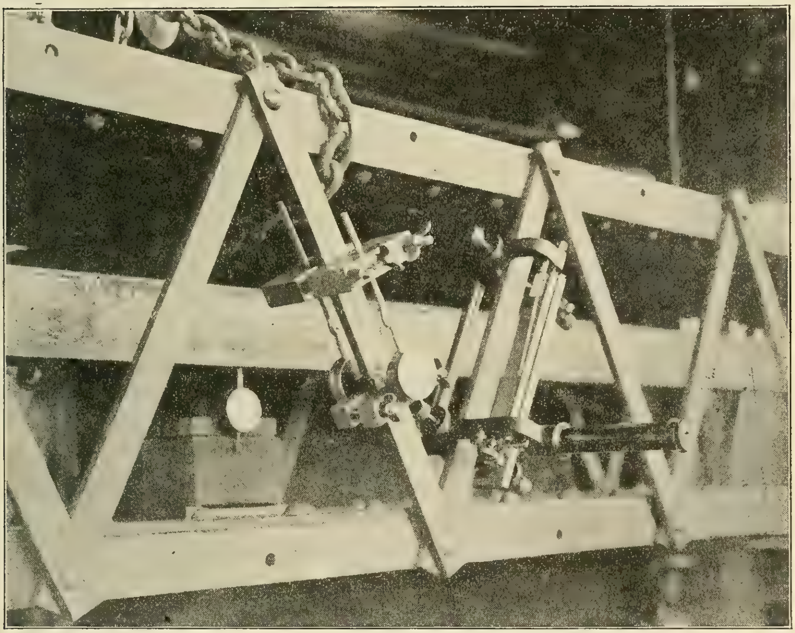

FIG. 6. EXTENSOMETERS IN PLACE ON LATTICE BARS OF COLUMN.

Fig. 5 shows the attachment of the Ames instruments to the channel members of a column, and Fig. 6 shows the attachment of both the Ames and the Ewing instruments to lattice bars.

The magnitude of error liable to be present in the determination of stresses from the readings of the extensometers was studied with some care. The accuracy of all the Ames gauges used was tested by comparison with a Brown and Sharpe micrometer acting through a 10 to 1 lever. The average deviation of a reading of the Ames dial was found to be $\frac{9}{100000}$ in. and the maximum observed deviation $\frac{3}{10000}$ in. The tests covered a range of motion of pointer slightly greater than that observed in the column tests. Basing judgment on the maximum deviation observed in calibration, and on the smallest deformation observed in the columns, it seems probable that the error in stress determination for the channel members is in all cases less than ± 10% and that in general it is much less. This general limit of accuracy is corroborated by a comparison of the average stresses at various cross-sections of the column as determined from the extensometer readings and from the load as indicated by the testing machine. To those accustomed to the apparently greater refinement of many laboratory tests and to the greater precision of calculations frequently employed, the above errors may seem unduly large. However, it may be considered that the instruments gave satisfactory results, especially in view of the large variation of stress

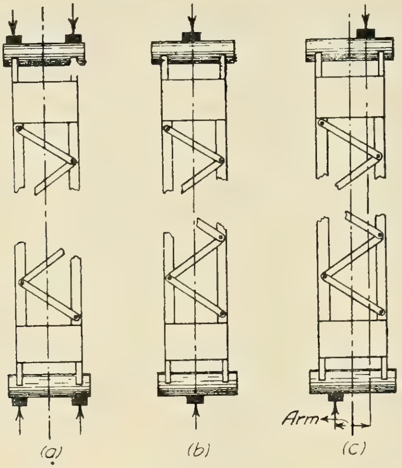

Fig. 7. Methods of Loading: (a) Regular Central Loading, (b) Central Loading, Column No. 2a and Column No. 1 for Tests No. 11, 12 and 14, (c) Oblique Loading, Column No. 2a, and Column No. 1 for Tests No. 12, 13, and 15.

distribution over the length of the columns, the general consistency of the results, and the fact that every stress determination is based on more than one reading and also that every conclusion is based on several stress determinations.

As noted above, the Ames test gauges were used to measure deformations in the lattice bars of the wrought-iron columns. On account of the very low stresses in the lattice bars it is felt that the stresses determined in them may be in error by ± 20%. In measuring the deformation of the lattice bars of Column No. 1 with a Ewing extensometer, the accuracy was greater, and the errors in determination of stress in lattice bars of Column No. 1 are probably not greater than ± 10%.

The Ames test gauges were light, durable, easily read, and adapted to a very wide range of conditions. In other tests they had successfuly withstood hard service. Any available instrument of greater precision would have been too bulky or too liable to injury or derangement of parts under the severe conditions of test, and especially under the conditions of field tests of columns.

9. *Procedure of Tests.*—The stress distribution was studied by measuring the compression or shortening over a short distance longitudinally. This measurement was made at several places in the cross-section. The dials were placed slightly outside the column, and the deformation along the extreme fibers of the channel members was later computed on the assumption for each channel member that a section plane before deformation remains plane after deformation. This hypothesis is not dependent upon the integrity of the column as a whole, but only upon that of the individual channel members. The position of the instruments at one location is shown in Fig. 5 (p. 12). As the elastic limit was not exceeded in the tests of stress distribution, in the interpretation of the data the stress in the piece is assumed to be proportional to the deformation. Necessary shifting of instruments and repetition of load made the test proceed very slowly. In studying the stress distribution of Column No. 1 for each method of loading it was necessary to apply the load about three hundred times. This took about three days of actual work after the column was adjusted in place. For each position of the instruments the load was applied and readings taken at least twice, frequently three times, and in cases where especially large readings, or especially small readings, were noted, five to ten readings were taken.

A similar procedure was followed in the tests of lattice bars in the study of stress distribution in them.

TABLE 2.

Stresses in Column No. 1.

Stresses are given in pounds per square inch.

Panel	North Channel						South Channel					
	West Side			East Side			West Side			East Side		
	Outer Fiber	Center of Gravity	Inner Fiber	Outer Fiber	Center of Gravity	Inner Fiber	Outer Fiber	Center of Gravity	Inner Fiber	Outer Fiber	Center of Gravity	Inner Fiber
Test No. 1.												
1	8 100	10 200	10 600	12 200	10 000	9 700	6 500	8 400	8 600	9 600	10 900	11 300
2	9 700	10 100	10 100	8 100	9 600	10 000	11 900	11 500	11 600	8 900	10 500	11 100
3	7 500	10 200	11 000	11 800	10 000	9 700	11 500	9 800	9 800	9 000	10 300	11 000
4	10 500	10 000	10 000	10 500	11 000	11 000	9 000	8 600	8 600	10 800	10 100	10 500
5	9 600	9 100	9 100	10 900	9 700	9 500	10 300	8 500	9 700	8 800	10 100	10 600
6	9 900	11 000	11 100	10 000	9 600	9 700	9 400	8 400	8 100	9 000	9 200	9 100
7	10 000	7 600	6 900	11 000	10 000	9 900	9 000	9 400	9 900	9 200	10 000	10 400
8	8 100	8 900	9 000	10 800	11 300	11 500	12 700	10 500	10 400	12 200	10 100	10 300
9	10 000	11 000	11 100	9 400	11 000	11 000	14 500	10 000	9 000	9 000	9 200	9 200
10	14 000	10 000	9 300	14 300	11 800	11 000	5 400	8 900	9 300	7 200	9 600	10 000
11	8 600	9 500	9 600	10 000	9 800	9 600	9 000	8 800	8 400	9 800	11 000	11 400
12	12 300	9 200	8 700	9 100	9 400	9 800	10 800	9 300	9 000	10 700	9 600	9 500
13	....	....	....	8 700	8 800	9 000	7 800	9 000	9 200	......	......	....
Test No. 2.												
6	11 500	12 100	12 100	11 500	10 000	9 500	9 100	9 000	9 300	5 800	7 500	7 700
7	12 200	12 600	12 700	14 600	13 500	13 300	5 900	7 500	8 000	8 300	9 500	9 500
8	11 300	12 500	12 800	12 400	12 500	10 600	7 800	8 200	8 300	7 500	10 300	10 700
9	14 800	13 300	12 700	9 500	10 500	10 600	11 800	7 300	7 000	10 300	8 400	8 300
10	9 000	10 200	10 400	16 200	10 500	9 600	7 800	10 500	11 400	9 000	8 400	8 500
11	15 200	10 200	9 700	13 700	11 600	11 500	7 600	8 100	8 300	5 000	6 300	8 600
12	10 300	11 900	12 300	12 700	11 600	11 500	9 400	8 200	7 700	7 000	7 500	9 700
13	13 200	11 800	11 700	9 900	10 500	10 800	7 500	8 600	9 100	6 300	6 300	8 400
Test No. 3.												
1	....	....	....	13 800	10 400	9 500	7 500	8 800	8 900	......	......	....
2	8 900	10 600	10 900	8 800	10 400	10 600	8 300	9 300	9 400	10 000	9 700	9 700
3	10 500	9 800	9 800	8 700	9 000	9 200	10 400	8 700	8 700	11 900	10 500	10 300
4	9 800	10 800	11 000	11 100	10 700	10 700	8 300	8 300	8 500	13 300	12 600	12 200
5	10 500	10 000	9 800	11 200	10 700	10 700	9 000	10 000	10 100	9 300	9 500	9 400
6	11 300	12 300	12 500	10 900	10 500	10 700	10 400	9 700	9 500	7 500	9 400	9 600
7	10 400	10 700	10 700	11 900	11 000	10 800	9 200	10 000	10 000	8 400	8 800	8 800
8	12 100	10 200	10 200	12 100	13 000	13 100	8 500	9 300	9 400	7 300	9 000	9 400
9	7 600	9 900	10 200	10 500	10 900	10 800	14 400	9 300	8 400	10 900	10 600	10 700
10	10 500	12 000	12 100	14 200	11 000	10 500	7 200	10 400	10 900	7 800	8 700	8 700
11	14 200	10 500	9 700	7 500	8 500	8 600	8 300	9 400	9 300	7 000	9 400	9 800
12	10 400	12 000	12 200	6 500	7 500	7 800	11 000	9 300	9 000	7 900	9 100	9 400
13	12 600	9 800	9 500	8 300	8 400	8 200	7 200	9 800	10 200	11 000	10 800	10 900

TABLE 2—(*Continued*).

STRESSES IN COLUMN NO. 1.

TEST NO. 4.

Panel	NORTH CHANNEL						SOUTH CHANNEL					
	West Side			East Side			West Side			East Side		
	Outer Fiber	Center of Gravity	Inner Fiber	Outer Fiber	Center of Gravity	Inner Fiber	Outer Fiber	Center of Gravity	Inner Fiber	Outer Fiber	Center of Gravity	Inner Fiber
1	....	....	....	....	....	....	....	....	....	......	......	......
2	11 300	10 8000	10 700	10 500	11 100	11 200	6 100	3 000	2 500	8 900	10 200	10 600
3	10 000	11 6000	11 600	10 100	11 100	11 100	8 400	8 500	8 500	12 000	11 300	11 100
4	11 200	12 3000	12 500	9 900	10 900	11 000	7 600	9 400	9 700	7 900	9 300	9 500
5	....	....	....	12 800	11 100	10 700	....	......	.....	10 700	10 200	10 100
6	10 100	5 400	4 500	12 800	10 700	10 300	6 500	8 900	9 500	......	......	......
7	8 000	10 600	11 000	10 200	9 700	9 700	....	......	......	8 700	8 500	8 600
8	9 800	12 000	12 400	9 700	10 000	10 100	9 000	9 400	9 400	10 300	11 300	11 400
9	11 500	10 600	10 400	....	....	....	8 500	10 700	10 900	7 900	11 100	11 500
10	8 600	8 300	8 100	6 800	8 700	9 100	10 800	7 500	7 000	9 300	10 700	11 000
11	....	....	....	....	....	....	9 500	9 000	8 900	13 000	12 700	12 600
12	10 900	10 400	10 300	10 700	9 900	9 600	....	......	......	......	......	......
13	11 000	10 700	10 700	11 100	10 600	10 500	7 300	9 800	9 600	12 700	11 900	11 800

TEST NO. 5.

Panel	NORTH CHANNEL						SOUTH CHANNEL					
	West Side			East Side			West Side			East Side		
	Outer Fiber	Center of Gravity	Inner Fiber	Outer Fiber	Center of Gravity	Inner Fiber	Outer Fiber	Center of Gravity	Inner Fiber	Outer Fiber	Center of Gravity	Inner Fiber
½	12 100	10 400	9 300	11 000	9 500	8 700	9 700	10 500	10 900	10 400	10 800	10 900
1	9 800	11 100	11 800	10 000	10 200	10 500	12 200	10 400	9 300	13 500	11 300	10 400
1½	7 900	8 500	8 600	5 800	8 200	8 900	7 300	8 400	8 900	7 400	7 900	8 300
2	11 800	11 400	11 100	10 900	10 600	10 600	8 500	8 600	8 700	9 800	10 200	10 400
2½	10 700	11 000	11 100	10 800	10 200	10 200	11 800	11 900	11 800	9 700	9 700	9 600
3	5 800	7 500	8 500	7 800	8 000	8 500	8 300	8 500	8 600	7 700	9 100	9 700
3½	8 000	8 100	8 500	7 400	8 100	8 500	7 800	8 600	9 000	7 500	7 600	7 700
4	15 400	13 000	12 400	13 500	13 000	12 800	11 600	11 800	11 800	9 900	9 900	9 900
4½	12 200	10 700	10 300	12 200	10 200	9 200	9 900	9 900	9 800	9 800	9 800	9 700
5	9 400	9 500	9 600	11 000	10 100	9 600	9 700	9 500	9 500	8 900	9 800	9 900
5½	9 900	10 700	11 100	10 500	10 900	11 000	10 900	9 100	8 300	8 700	8 800	8 900
6	7 400	7 300	7 200	8 100	9 200	9 700	13 800	11 900	11 100	11 100	10 600	10 200
6½	10 900	10 200	9 700	10 200	10 300	10 500	8 600	8 900	8 900	8 500	8 600	8 600
7	12 100	11 700	11 400	11 400	10 900	10 400	8 300	8 800	8 900	5 900	7 900	8 700
7½	9 900	9 200	8 900	9 600	9 400	9 500	6 500	7 600	8 300	4 600	6 400	6 900
8	9 800	8 600	8 300	8 100	9 700	10 400	11 400	9 500	8 500	12 700	10 800	10 100
8½	9 200	9 700	10 000	9 700	9 500	9 300	20 200	15 400	13 100	15 400	14 000	13 200
9	6 500	7 600	8 300	9 700	9 700	9 900	12 900	13 200	13 100	9 400	9 900	10 200
9½	10 000	10 400	10 600	12 900	9 500	8 100	4 600	7 800	8 900	4 600	7 300	8 500
10	16 400	12 900	11 200	17 000	14 400	12 900	8 000	8 600	8 700	6 800	8 000	8 600
10½	11 300	10 700	10 400	9 900	10 000	9 700	10 500	11 100	11 300	7 400	8 900	9 600
11	7 000	8 400	8 900	8 100	9 100	9 600	12 600	11 100	10 800	9 800	10 800	11 000
11½	9 700	8 900	8 600	11 900	10 500	9 700	8 200	11 100	11 700	8 900	9 700	9 800
12	14 000	12 400	11 600	11 900	11 000	10 400	6 900	7 500	7 800	8 100	8 800	9 400
12½	9 700	8 900	8 600	10 500	12 100	12 700	10 800	11 800	12 400	11 900	11 000	10 800

TABLE 3.

STRESSES IN WROUGHT-IRON BRIDGE POSTS.

Panel	NORTH CHANNEL						SOUTH CHANNEL					
	West Side			East Side			West Side			East Side		
	Outer Fiber	Center of Gravity	Inner Fiber	Outer Fiber	Center of Gravity	Inner Fiber	Outer Fiber	Center of Gravity	Inner Fiber	Outer Fiber	Center of Gravity	Inner Fiber
COLUMN NO. 2, TEST NO. 6.												
1	4 600	6 500	7 300	6 400	7 900	8 500	4 300	8 300	9 700	5 000	6 800	7 400
2	7 300	7 300	7 300	8 300	8 400	8 400	9 800	9 000	8 800	9 000	8 000	7 600
3	5 500	5 900	6 000	7 100	7 800	8 000	7 700	8 800	9 200	6 700	7 600	7 900
4	6 200	6 100	6 200	6 100	6 900	7 100	8 400	8 800	9 000	8 200	8 000	8 000
5	7 200	6 500	6 100	8 800	8 600	8 500	7 500	8 800	9 300	8 700	7 800	7 500
6	6 800	6 900	6 900	8 400	8 400	8 400	7 100	7 600	7 800	6 900	7 200	7 400
7	7 500	7 900	8 000	7 100	7 400	7 500	7 500	8 200	8 500	7 500	7 400	7 300
8	6 400	7 400	7 800	6 200	7 200	7 600	7 700	7 900	8 000	6 600	6 400	6 100
COLUMN NO. 3, TEST NO. 7.												
1	9 300	9 000	9 000	8 400	9 500	10 000	10 000	9 000	10 100	8 200	8 000	7 900
2	10 200	10 000	9 900	10 200	11 500	11 900	8 400	9 100	10 000	9 100	8 700	8 500
3	8 800	8 700	8 600	9 800	10 000	10 000	10 000	9 700	9 600	9 400	9 600	9 600
4	10 500	9 100	8 600	8 500	9 500	9 900	8 600	9 800	10 200	9 300	7 500	6 900
5	10 200	10 400	10 500	8 800	9 600	9 900	10 100	9 800	9 700	10 400	10 200	10 200
6	10 600	10 000	9 800	10 300	10 000	10 000	10 400	10 400	10 400	10 000	9 900	9 900
7	10 300	9 900	9 700	9 600	9 900	10 000	8 700	9 500	9 700	10 900	10 000	9 700
8	9 800	9 600	9 500	10 200	10 900	11 000	7 600	9 600	10 300	7 800	9 900	10 600
COLUMN NO. 4, TEST NO. 8.												
1	9 000	9 800	10 000	10 000	10 700	11 000	8 200	10 000	10 800	9 000	9 200	9 300
2	8 700	9 300	9 500	10 100	10 800	11 100	10 100	11 600	12 100	8 600	9 400	9 700
3	9 300	9 800	9 900	10 800	11 200	11 400	10 000	10 200	10 200	7 400	8 400	8 700
4	9 500	9 700	9 800	11 100	10 200	10 000	9 700	11 100	11 600	7 100	8 200	8 500
5	10 200	10 500	10 600	11 900	12 400	12 600	8 400	9 400	9 800	7 700	8 800	9 200
6	11 600	12 000	12 100	12 400	13 600	13 900	9 500	10 800	11 100	7 400	9 500	10 200
7	12 800	12 500	12 400	13 400	14 200	14 600	7 100	8 300	8 700	6 400	6 700	6 700
8	8 600	11 600	12 700	13 000	11 300	10 700	6 600	8 500	9 200	6 200	7 800	8 400
COLUMN NO. 5, TEST NO. 9.												
½	14 000	11 700	10 800	12 600	11 700	11 400	7 400	8 100	8 400	7 400	7 900	8 000
1	11 300	12 000	12 300	11 100	10 000	9 600	6 700	8 500	9 200	5 100	6 800	7 500
1½	11 300	11 100	11 100	11 100	10 800	10 700	5 700	6 200	6 300	6 600	6 900	7 100
2	13 100	12 600	12 400	12 900	12 400	12 200	8 000	8 000	8 000	7 800	8 200	8 300
2½	12 700	12 000	11 700	13 100	11 500	11 100	9 300	9 200	9 200	8 700	8 400	8 300
3	11 800	12 000	12 200	11 400	12 200	12 400	8 200	8 400	8 400	6 300	8 000	8 600
3½	13 500	10 500	9 300	11 600	10 700	10 400	8 200	8 200	8 200	8 400	8 300	8 200
4	14 300	13 100	12 700	14 300	12 300	11 500	7 300	7 400	7 500	7 400	8 700	9 200
4½	11 600	11 600	11 500	12 300	12 300	12 300	9 000	9 000	9 000	8 700	8 700	7 800
5	12 600	12 400	12 300	11 700	10 400	10 000	8 300	8 400	8 400	7 400	8 500	8 100
5½	13 700	12 100	11 500	13 500	12 100	11 400	8 300	8 300	8 300	8 400	8 400	7 600
6	12 600	12 700	12 700	13 500	12 500	12 200	7 600	7 600	7 600	7 200	7 000	7 100
6½	13 100	11 900	11 500	11 400	11 400	11 500	8 400	8 400	8 400	10 500	9 000	8 500
7	11 100	11 300	11 500	11 200	12 300	12 600	7 900	8 000	8 000	6 500	8 100	8 600
7½	10 600	10 100	9 900	11 000	10 300	9 900	8 000	8 200	8 200	5 900	7 900	8 700
8	10 300	12 300	12 800	11 300	12 300	12 400	8 500	8 600	8 600	10 800	11 800	12 200

TABLE 3—(*Continued*).

COLUMN NO. 4a, TEST NO. 10.

Panel	NORTH CHANNEL						SOUTH CHANNEL					
	West Side			East Side			West Side			East Side		
	Outer Fiber	Center of Gravity	Inner Fiber	Outer Fiber	Center of Gravity	Inner Fiber	Outer Fiber	Center of Gravity	Inner Fiber	Outer Fiber	Center of Gravity	Inner Fiber
½	8 100	9 500	10 200	8 400	8 100	8 000	11 700	10 800	10 500	9 900	11 200	11 800
1	8 300	10 200	10 800	6 500	7 200	7 500	12 100	10 900	10 400	11 100	12 500	13 100
1½	8 400	9 400	9 700	7 400	8 200	8 400	12 100	11 400	11 100	11 000	11 400	11 600
2	8 700	8 800	9 000	6 200	7 200	7 500	10 800	10 500	9 700	9 300	11 700	12 600
2½	8 300	8 800	9 000	7 300	6 900	6 800	11 800	11 500	12 100	10 900	10 400	10 300
3	8 700	9 700	9 900	6 700	6 500	6 400	13 300	11 100	10 400	10 400	11 100	11 400
3½	8 300	8 000	8 000	7 300	7 300	7 400	13 600	11 600	11 100	13 000	12 400	12 400
4	8 200	9 700	10 100	6 800	6 900	6 800	14 300	13 500	12 700	13 100	11 100	10 500
4½	7 500	8 600	9 100	6 300	7 200	7 500	12 300	11 100	10 800	10 300	15 200	9 400
5	7 500	8 400	8 800	7 000	8 100	8 500	13 000	13 300	13 500	9 000	11 400	12 300
5½	6 300	7 200	7 500	5 900	6 100	6 200	12 700	12 300	12 100	12 300	10 700	10 100
6	6 800	7 800	8 200	5 300	6 800	7 200	14 200	14 200	14 200	11 000	11 200	11 300
6½	6 600	7 800	8 200	7 100	7 100	7 100	15 400	13 700	12 900	13 500	11 500	11 100
7	6 700	7 100	7 200	4 900	6 100	6 700	11 900	13 600	14 600	11 100	12 100	12 400
7½	6 100	7 600	8 300	4 800	8 100	9 400	12 300	12 400	12 400	9 300	16 200	11 100
8	6 000	8 200	9 000	8 400	6 800	6 200	10 700	12 200	12 800	10 000	16 300	11 100

COLUMN NO. 2a, TEST NO. 11.

Panel	NORTH CHANNEL						SOUTH CHANNEL					
	West Side			East Side			West Side			East Side		
	Outer Fiber	Center of Gravity	Inner Fiber	Outer Fiber	Center of Gravity	Inner Fiber	Outer Fiber	Center of Gravity	Inner Fiber	Outer Fiber	Center of Gravity	Inner Fiber
½	11 600	10 900	10 400	11 400	10 500	10 000	....	....	....	....	....	....
1	7 300	9 300	10 000	7 300	9 700	10 400	8 400	8 800	9 000	10 200	10 200	10 200
1½	11 600	9 900	9 600	11 600	10 900	10 000	8 500	10 000	10 600	11 400	12 000	12 200
2	8 900	8 700	8 600	10 500	10 300	10 000	10 200	9 000	8 600	11 500	11 200	11 000
2½	11 200	9 700	9 200	10 900	10 300	10 000	9 900	10 000	10 200	11 700	10 300	9 900
3	9 500	10 500	10 700	12 200	10 800	10 000	11 800	10 200	10 800	11 400	10 600	10 300
3½	10 500	11 000	11 000	12 100	10 600	10 000	10 400	8 600	8 100	9 700	9 600	9 400
4	9 800	9 500	9 400	10 600	9 900	9 600	9 800	9 400	9 200	10 400	10 600	10 500
4½	10 300	9 600	9 300	11 200	10 200	10 000	8 700	9 600	10 400	10 400	10 000	10 000
5	9 600	9 800	9 900	10 400	10 800	11 000	10 300	9 200	8 800	10 400	10 200	10 200
5½	12 200	11 600	11 200	12 000	11 100	10 700	12 500	10 400	10 000	12 200	11 900	11 700
6	10 100	9 700	9 700	9 900	9 700	9 700	9 100	10 400	10 900	10 300	10 700	10 700
6½	11 300	11 000	10 800	10 600	9 900	9 700	10 800	9 900	9 700	11 000	11 000	10 000
7	9 300	9 600	9 700	9 100	9 300	9 200	9 800	9 800	9 800	9 800	10 800	10 000
7½	10 200	10 900	11 400	9 100	9 400	9 500	9 300	9 600	9 800	9 900	10 700	10 800
8	9 900	9 800	9 700	11 100	10 000	9 600	8 800	10 300	10 900	10 800	10 700	10 800

COLUMN NO. 2a, TEST NO. 12.

Panel	NORTH CHANNEL						SOUTH CHANNEL					
	West Side			East Side			West Side			East Side		
	Outer Fiber	Center of Gravity	Inner Fiber	Outer Fiber	Center of Gravity	Inner Fiber	Outer Fiber	Center of Gravity	Inner Fiber	Outer Fiber	Center of Gravity	Inner Fiber
½	10 600	10 000	9 800	10 400	10 600	10 600	11 500	10 600	10 000	13 200	12 600	12 300
1	8 400	8 400	8 500	9 700	10 800	11 200	9 800	10 700	10 900	10 000	11 300	11 700
1½	8 200	8 000	7 900	9 200	10 600	10 900	9 200	9 600	9 700	8 800	10 000	10 200
2	9 200	9 800	10 000	9 900	10 900	11 300	11 400	10 000	9 400	12 200	11 400	11 000
2½	10 800	9 900	9 600	10 800	9 600	9 100	10 900	10 900	10 900	11 400	11 600	11 600
3	9 100	10 ~~800~~	11 200	11 000	10 600	10 400	10 600	11 200	11 300	10 400	10 200	10 100
3½	10 700	10 900	10 800	12 000	10 600	10 000	10 600	10 900	10 900	10 200	10 600	10 600
4	10 000	8 800	8 400	11 400	9 400	9 400	8 900	10 000	10 300	8 800	10 300	10 900
4½	10 600	10 000	9 900	10 200	10 000	9 900	10 000	10 100	10 200	8 600	9 500	9 800
5	10 100	10 300	10 400	11 300	11 000	11 000	11 800	10 200	9 600	10 200	9 700	9 700
5½	10 900	11 300	11 300	11 400	10 600	10 300	13 000	11 000	10 400	11 000	9 500	9 000
6	11 500	10 800	10 500	9 500	9 000	9 000	9 500	9 900	10 000	9 700	9 500	9 500
6½	11 700	9 800	9 200	12 700	10 300	9 600	10 000	10 000	10 000	9 600	10 300	10 600
7	9 900	11 300	11 600	9 900	11 100	10 600	10 500	9 800	9 300	9 600	10 000	10 000
7½	8 000	9 700	10 300	15 400	15 400	15 400	7 800	10 000	10 600	6 800	8 500	9 000
8	10 000	9 800	9 900	11 700	10 100	9 900	8 800	10 400	11 100	9 400	9 400	9 400

TABLE 3—(*Continued*).

COLUMN NO. 2a, TEST NO. 13.

Panel	North Channel						South Channel					
	West Side			East Side			West Side			East Side		
	Outer Fiber	Center of Gravity	Inner Fiber	Outer Fiber	Center of Gravity	Inner Fiber	Outer Fiber	Center of Gravity	Inner Fiber	Outer Fiber	Center of Gravity	Inner Fiber
1	4 500	7 000	8 600	7 000	8 600	9 100	9 800	10 800	11 100	10 300	12 300	13 000
2	7 600	9 000	9 500	10 300	10 400	10 600	10 900	10 100	9 700	12 800	12 600	12 600
3	7 000	8 600	9 100	9 400	10 100	10 300	11 300	11 300	11 300	11 600	12 600	13 000
4	8 100	9 100	9 500	10 400	10 800	10 900	9 300	10 400	10 700	9 600	11 600	12 500
5	8 200	9 500	10 000	10 000	10 200	10 200	10 900	8 900	8 100	10 600	10 700	10 800
6	10 000	10 400	10 600	10 500	10 000	10 000	8 500	9 600	10 000	9 600	10 400	10 800
7	9 800	9 800	9 900	10 200	10 300	10 300	9 500	8 800	8 700	9 900	10 000	10 100
8	8 000	7 800	7 700	12 300	10 300	9 200	7 700	8 700	9 100	8 700	10 000	10 500

10. *Method of Loading.*—Two methods of loading were used, central and oblique. In all cases the load was applied to the end of the column through the pins, and in a plane passing through the nominal axis of the column and paralled to the lacing. In central loading the pin was adjusted to an even bearing on the machine. In oblique loading the pin was supported on a narrow block as shown in Fig. 7 in such a way as to secure a given eccentricity. The center of the block was taken as the point of application of the load. This assumption is approximately correct, the error being probably not greater than ¼ in. In two tests of Column No. 1, the point of application of load is somewhat uncertain, as by an oversight the two bearing blocks were not placed symmetrically with respect to the axis of the column. Probably the loading was nearly central.

11. *Routine of Tests for Stress Distribution.*—In a test for stress distribution, the column was placed in the machine and a light initial load was applied. The extensometers were then attached in position to measure the deformation at some point of the column, and an initial reading was taken. A known load was applied by the testing machine and the instruments were read again. The load was then released to its initial value and another application of the load was made. If the second readings did not exactly check the first, further applications of the load were

made. In cases where the observed deformations were large or seemingly abnormal, the test was repeated at another time, and in some cases as many as ten observations were made on the same gauged length. In some of these cases the instruments were reset, their places being exchanged. The instruments were next attached in a new location, and the process was repeated. Thus the stress distribution in various parts of the column was finally determined.

The above method of changing instruments from position to position is practically necessary, as the expense of providing a sufficient number of extensometers to measure the deformation in every panel of the column would be very great.

The load generally used in the laboratory tests was 10 000 lb. per sq. in. of section of the column in excess of the initial load.

12. *Results of Tests for Stress Distribution.*—Tables 2 and 3 give results of the tests to determine stress distribution and variation in the flange members found in thirteen of the column tests. The stresses given are calculated from the observed deformation, using for the modulus of elasticity 28 000 000 lb. per sq. in. for steel and 26 000 000 lb. per sq. in. for wrought-iron, these values checking closely with the total shortening of the columns and with the average deformations observed throughout their length. As heretofore described, the stress noted is the average over a space of 4 in. or 4½ in. on either side of the point indicated. Any lack of agreement between the average stress on the center of gravity of the flange members and the average stress for the load applied is probably due principally to instrumental errors.

Fig. 8 to 15 show graphically the stress distribution and variation. The full line gives the stress at the east side (back) and the dotted line at the west side (front).

Table 4 gives a number of the most marked deviations from average stress. The excess of the maximum fiber stress is given as a percentage of the average stress.

In most cases the maximum stress was in the outer fiber of the channel; sometimes very high stresses were found in the inner fiber. Generally, the stress in the opposite channel was correspondingly less.

13. *Stress in Lattice Bars.*—Table 5 gives the results of tests to determine the average stress in the various lattice bars of the columns. Tests 14 and 15 were tests on the lattice bars only.

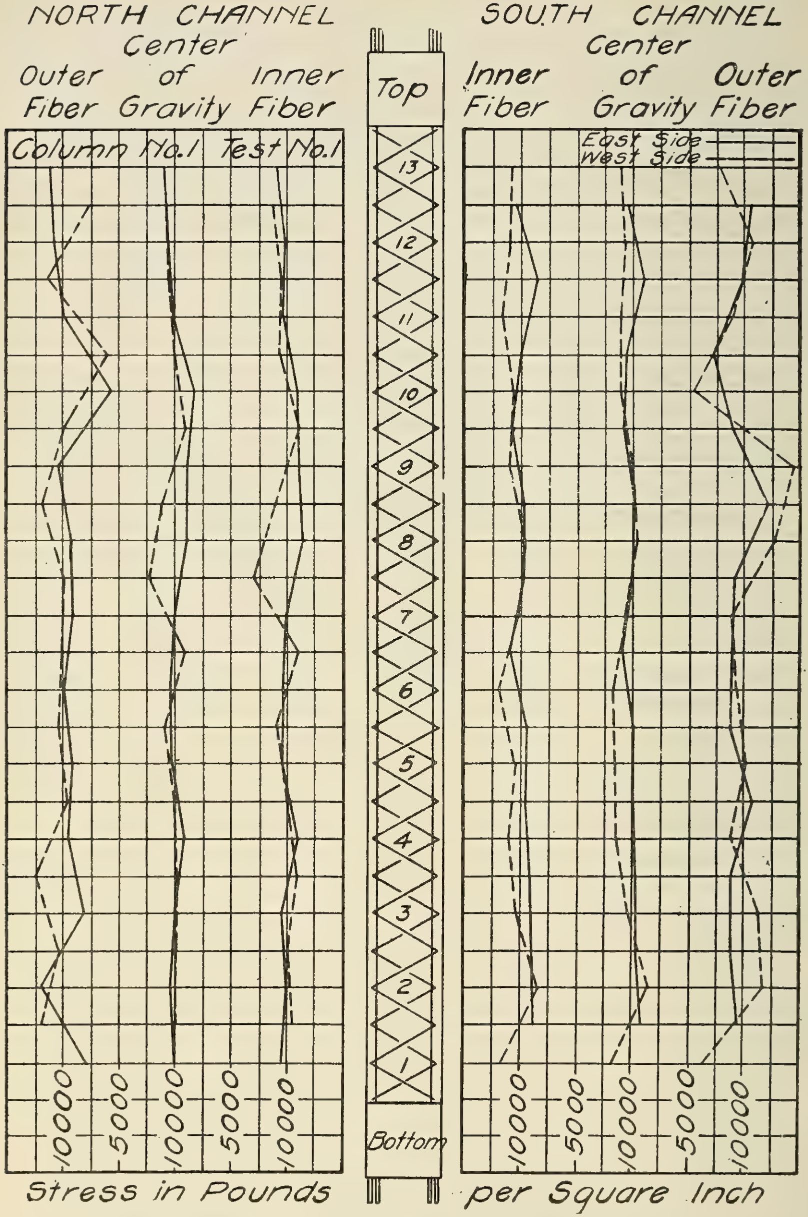

FIG. 8. STRESS DISTRIBUTION IN CHANNELS OF COLUMN NO. 1, TEST NO. 1.

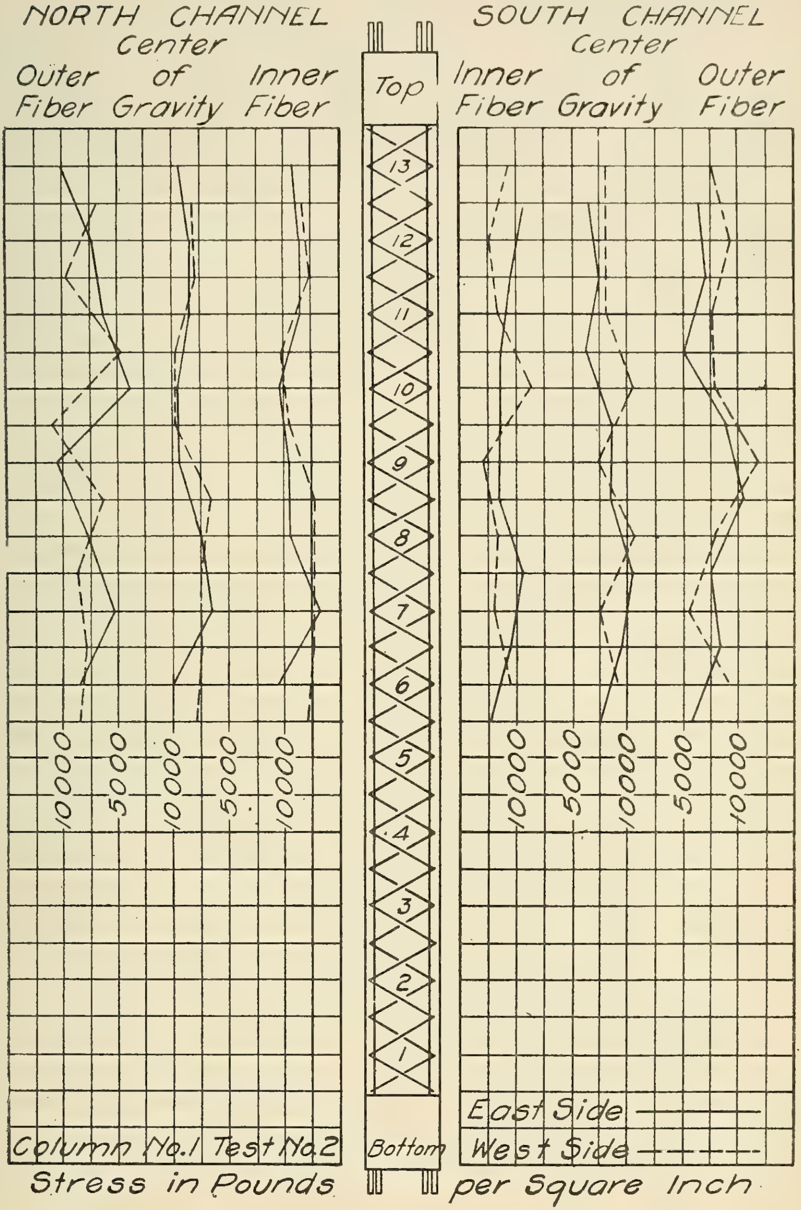

FIG. 9. STRESS DISTRIBUTION IN CHANNELS OF COLUMN NO. 1, TEST NO. 2.

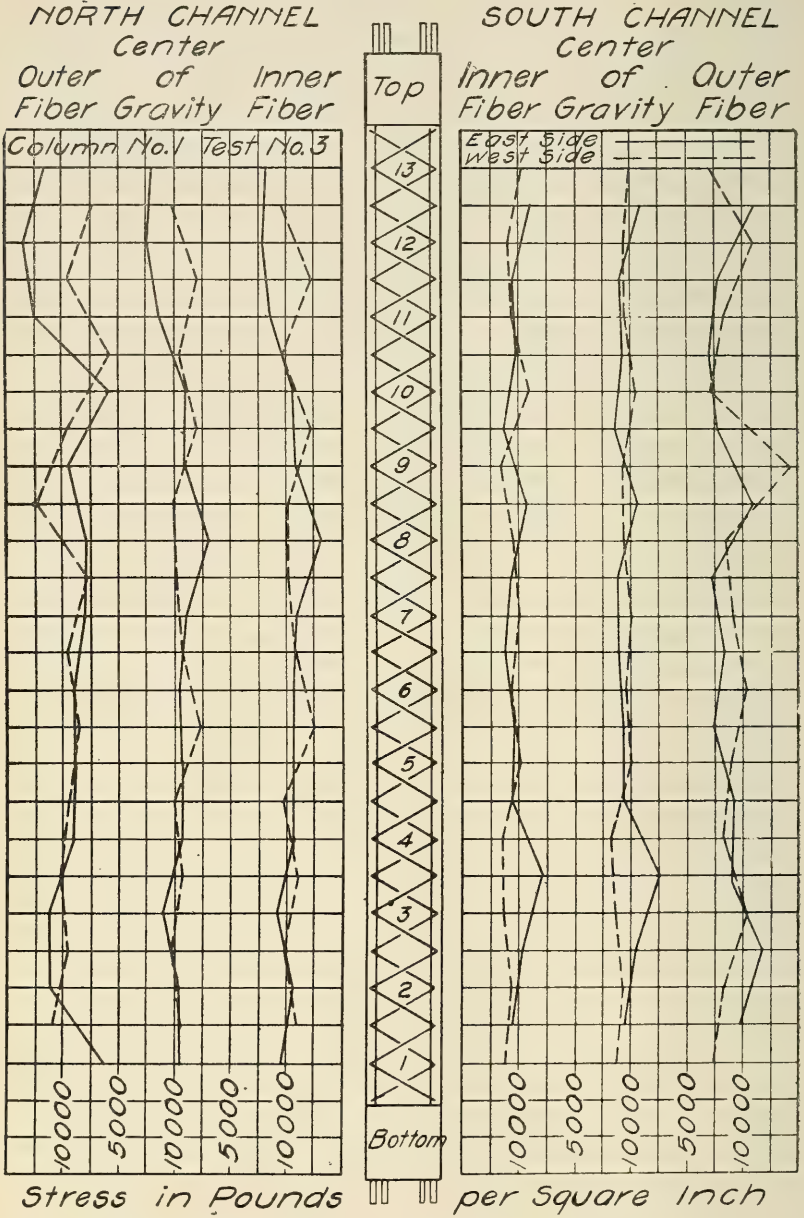

FIG. 10. STRESS DISTRIBUTION IN CHANNELS OF COLUMN NO. 1, TEST NO. 3.

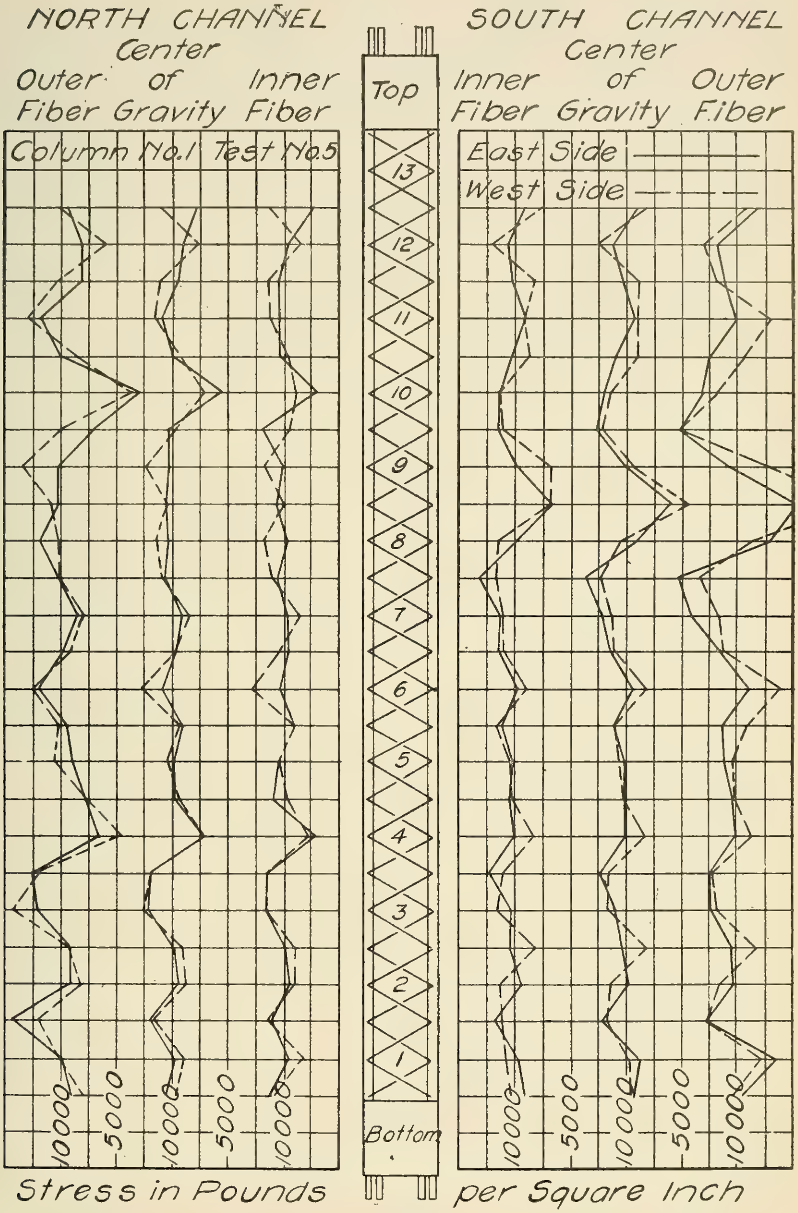

FIG. 11. STRESS DISTRIBUTION IN CHANNELS OF COLUMN NO. 1, TEST NO. 5.

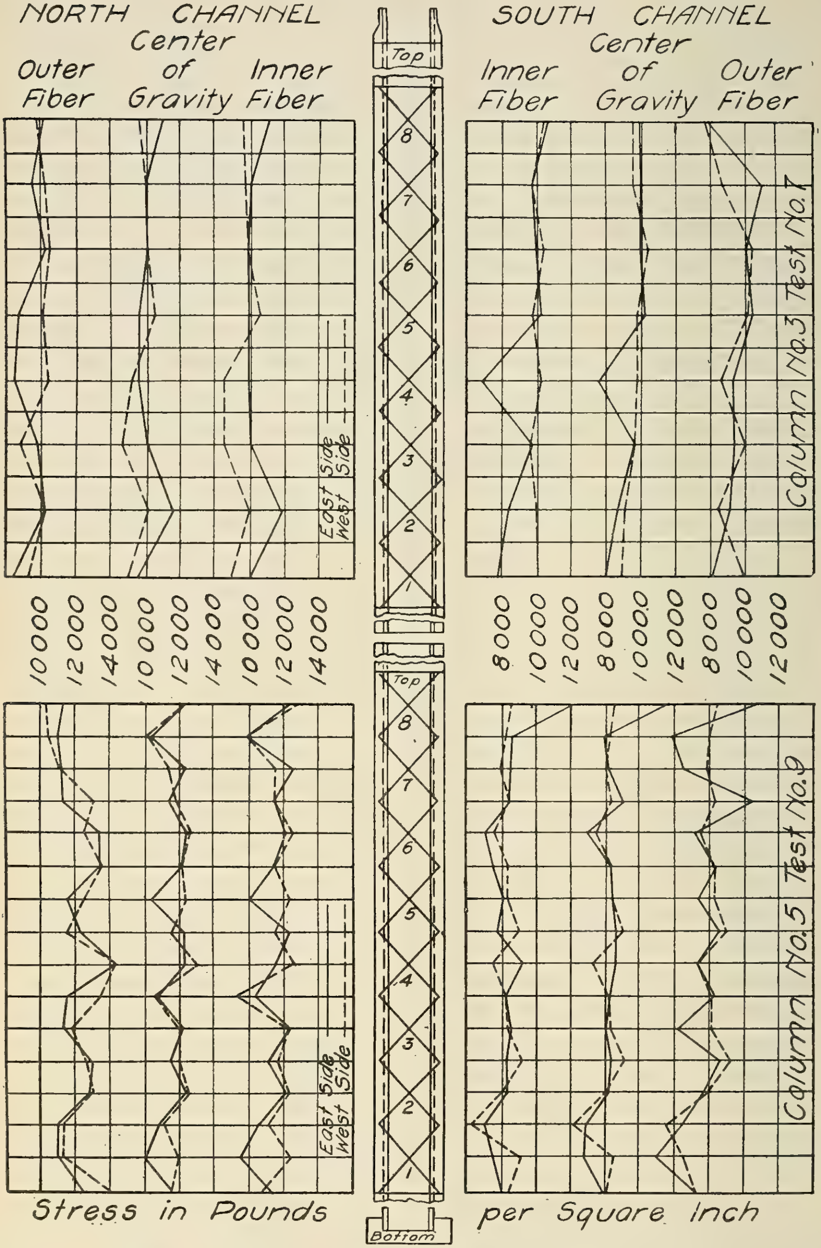

FIG. 12. STRESS DISTRIBUTION IN CHANNELS OF COLUMNS NO. 3 AND 5.

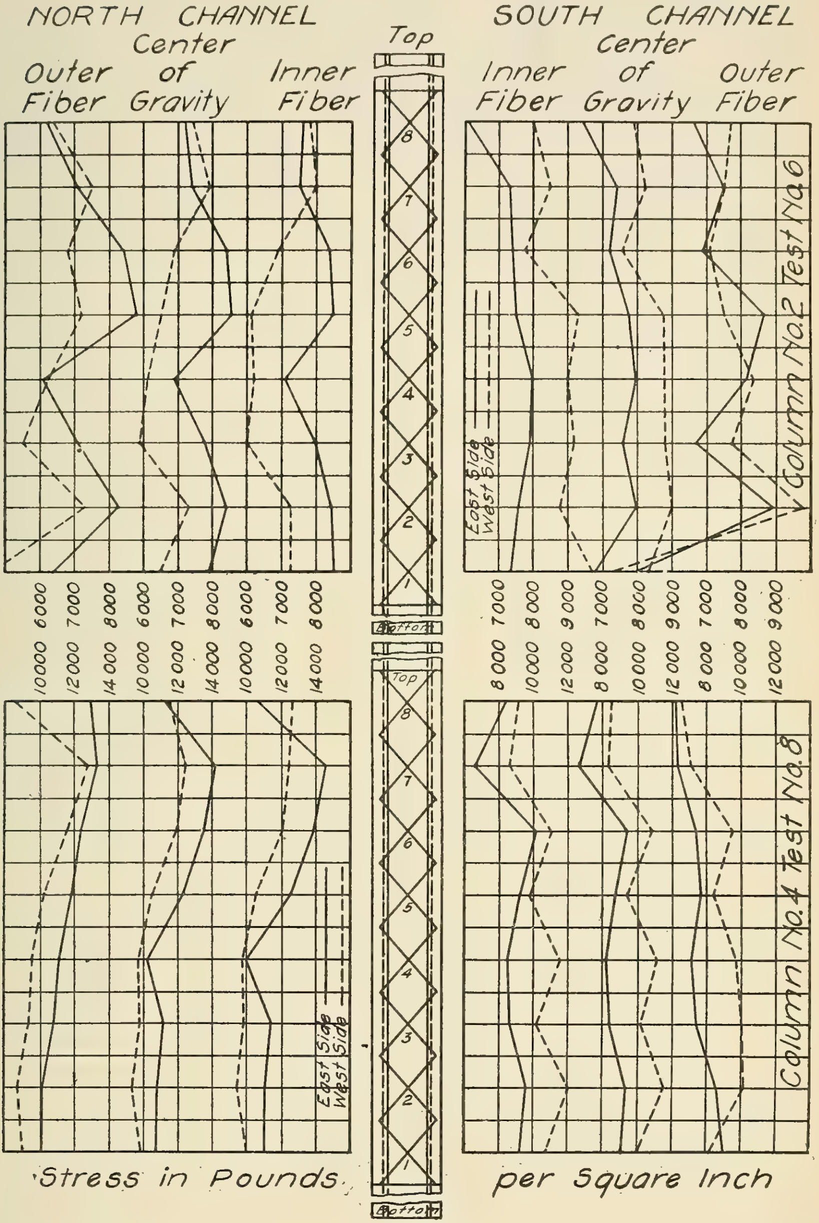

FIG. 13. STRESS DISTRIBUTION IN CHANNELS OF COLUMNS NO. 2 AND 4.

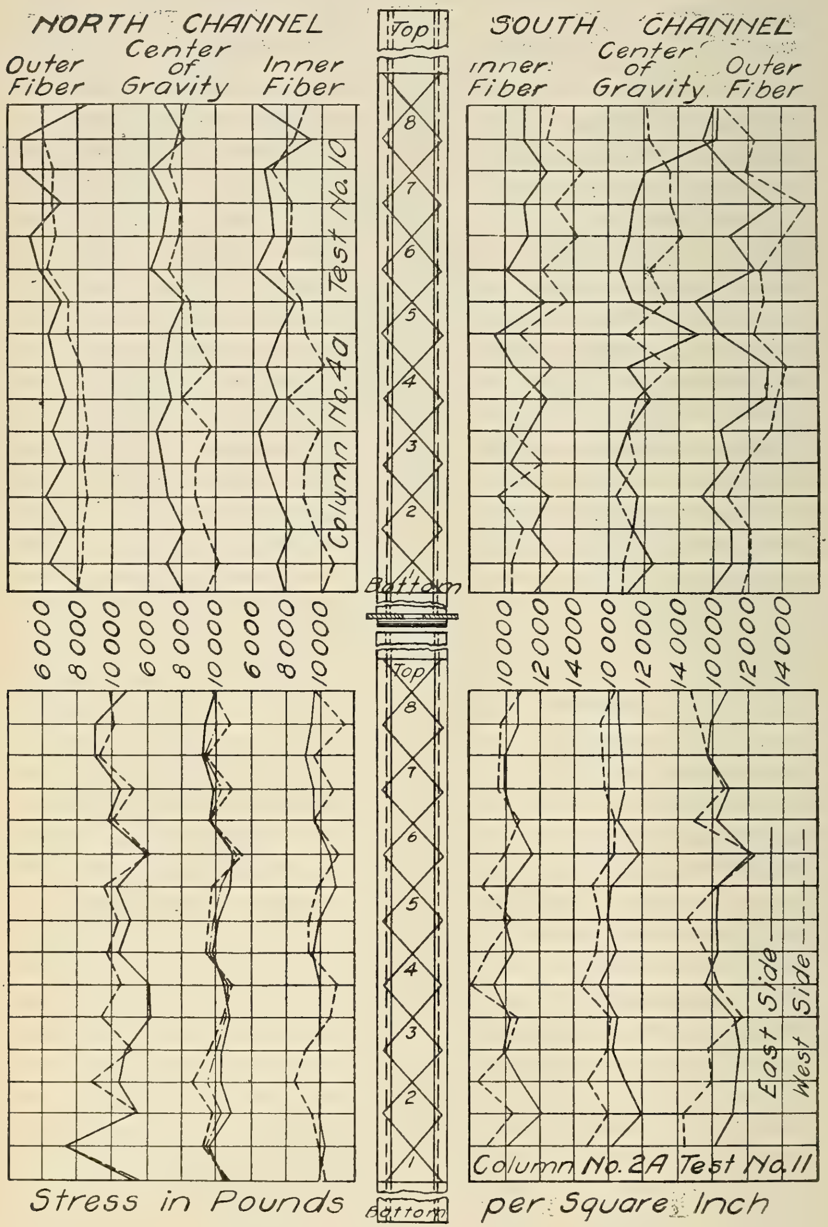

FIG. 14. STRESS DISTRIBUTION IN CHANNELS OF COLUMNS NO. 2a AND 4a.

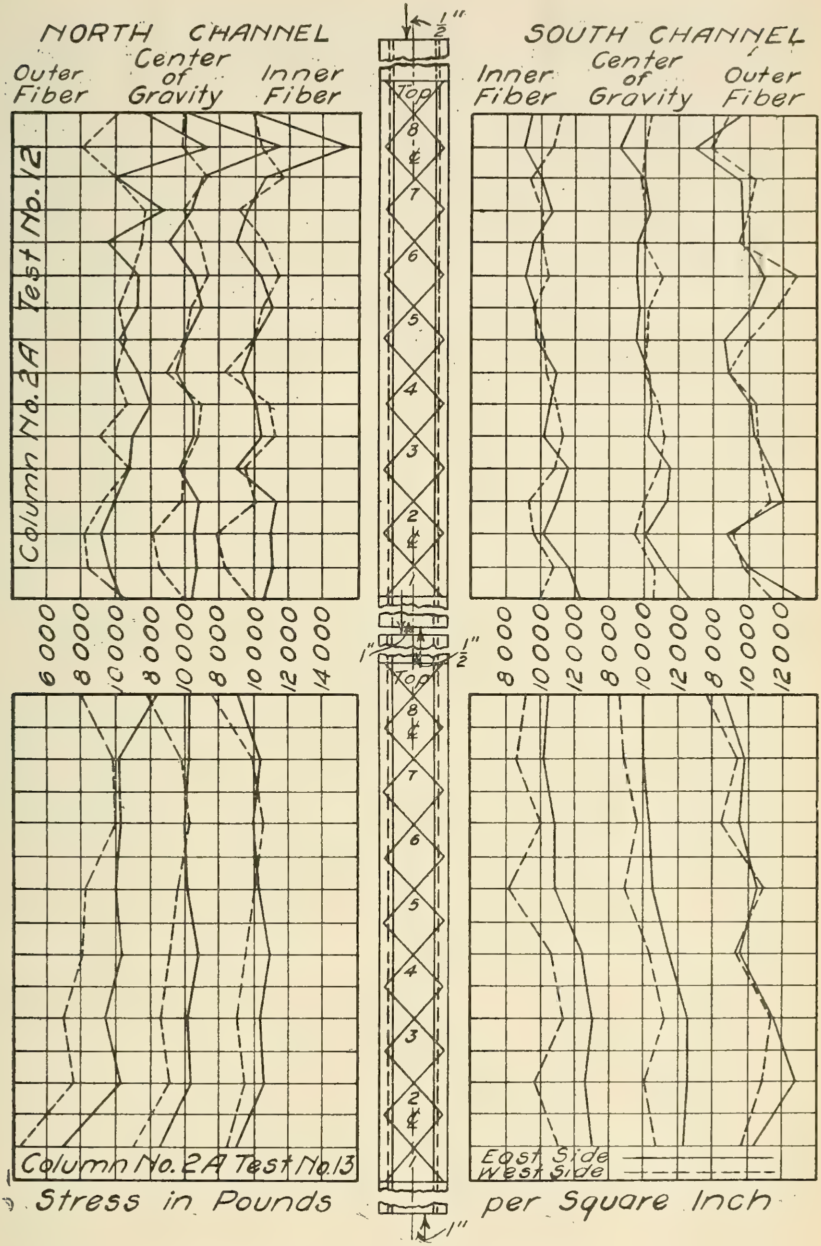

FIG. 15. STRESS DISTRIBUTION IN CHANNELS OF COLUMN NO. 2a.

The distribution of stress over the cross-section of the bar is discussed in another place. The average stresses in the lattice bars are computed from the observed deformation, using a modulus of

TABLE 4.

Maximum Observed Fiber Stresses in Flange Members of Columns.

Col. No.	Test No.	Feature of Lacing	Method of Loading	Excess of Maximum Fiber Stress over Average Stress per cent Highest five values
1	1	1¼ × $\frac{7}{16}$ in. bolted	Central	42,41,39,31,23
1	2	"	Slightly eccentric	68,64,50,49,35
1	3	"	"	50,41,35,32,19
1	4	1 × ¼ in. bolted	Central	35,29,28,27,26
1	5	1 × ¼ in.	"	67,55,49,29,27
2	6		"	31,23,23,21,17
3	7		"	20,17,12,11, 9
4	8		"	41,29,24,22,19
5	9		"	43,43,38,35,35
4a	10		"	53,49,42,40,37
2a	11		"	21,16,13,12,11
2a	12		Oblique (Fig. 6) Arm 1 in.	42,42,24,23,20
2a	13		Oblique (Fig. 6) Arm 2 in.	35,34,22,21,21

TABLE 5.

Total Stress in Pounds on Lattice Bars under Load on Columns of 10 000 lb. per sq. in.

c denotes compressive stress; t, tensile stress.

Lattice Bar	Test 5		Test 14		Test 15	
	Front	Back	Front	Back	Front	Back
1	400c	400c	300t	400t	—	—
2	100t	600t	1600t	400c	—	—
3	0	600c	800c	400t	—	—
4	100t	400t	300t	100c	—	—
5	100c	100c	—	—	—	—
6	200t	300t	—	—	—	—
7	100c	200c	—	—	—	—
8	200t	200t	—	—	—	—
9	0	300c	—	—	—	—
10	0	200t	—	—	—	—
11	100c	300c	—	—	—	—
12	0	100t	—	—	—	—
13	100c	200c	800c	0	—	—
14	100t	200t	900t	900t	2500t	1600c
15	0	300c	200c	1000t	2100c	—
16	0	400t	800t	0	1600t	200c
17	200c	200c	500c	300t	1900c	—
18	200t	100t	700t	1000t	700t	1100t
19	500c	200c	500c	200t	1500c	—
20	200t	300t	800c	200t	1400t	700t
21	0	600c	800c	600t	1500c	0
22	100c	2000t	0	200t	700t	300t
23	200t	900c	300c	800c	1300c	—
24	200c	800t	200t	800t	600t	400c
25	200t	800c	0	0	2700c	—
26	200c	700t	400t	300c	400t	400c

TABLE 5—(*Continued*).

TOTAL STRESS IN POUNDS ON LATTICE BARS UNDER LOAD ON COLUMNS OF 10 000 LB. PER SQ. IN.

Lattice Bar	Front Side		Back Side	
	Under	Over	Under	Over
	Column 2a,	Test 11.	Column 2a,	Test 11.
1	700c	700c	1300c	100c
2	100c	100t	200t	200t
3	3000t	0	1000t	0
4	100c	100c	800c	200c
5	3000t	0	800c	300c
6	200t	200c	0	300c
7	3700t	0	200t	200c
8	0	800c	800c	300c
	Column 2a,	Test 12.	Column 2a,	Test 12.
1	1500c	2100t	200c	200c
2	200c	400t	2300t	200c
3	800t	200t	2750t	400c
4	700c	500t	2750t	300c
5	1600t	200t	2750t	300c
6	0	0	2800t	800c
7	1400t	800c	4100t	300c
8	100t	800c	300t	800c
	Column 2a,	Test 13.	Column 2a,	Test 13.
1	1000c	700t	800t	500c
2	500c	700t	2650t	400c
3	700c	900t	2750t	300c
4	500c	1000t	2100t	200t
5	800c	600t	3150t	1000c
6	1000c	700t	4100t	700c
7	700c	900t	1500t	400c
8	1600c	200c	2000t	1400c

elasticity of 28 000 000 lb. per sq. in. for the steel column and 26 000 000 lb. per sq. in. for the wrought-iron columns. As might be expected, from the irregular variation of stress along the flange members of the columns, the stress in the lattice bars was found to vary greatly.

Table 6 gives the largest stresses observed and the corresponding transverse shear. The transverse shear given in this table is that which would cause a stress in the lattice bars equal to the maximum stress observed in any lattice bar, and was computed by doubling the transverse component of the maximum load observed on a lattice bar. In the case of obliquely loaded columns, the transverse component of the load was computed on the assumption that the load was applied through the center of the bearing blocks. This transverse component was then subtracted from the amount of shear which has been calculated from the def-

TABLE 6.

MAXIMUM OBSERVED AVERAGE STRESS IN LATTICE BARS OF COLUMNS NO. 1 AND 2a.

Column number	1	1	1	2a	2a	2a
Test number	5	14	15	11	12	13
Method of loading	Central	Central	Oblique (Fig. 6) Arm 4 in.	Central	Oblique (Fig. 6) Arm 1 in.	Oblique (Fig. 6) Arm 2 in.
Total load, pounds	187 600	187 600	187 600	176 400	176 400	176 400
Lacing	Single 63° 30′ with axis, 1×¼ riveted	Single 63° 30′ with axis, 1¼×$\frac{7}{16}$ riveted	Single 63° 30′ with axis, 1¼×$\frac{7}{16}$ riveted	Double 45° 2½×⅜ riveted	Double 45° - 2½×⅜ riveted	Double 45° 2½×⅜ riveted
Maximum observed average stress in lattice bar, lb. per sq. in	8200	3000	4900	3900	4350	4350
Corresponding total stress in bar, pounds	2000	1600	2700	3700	4100	4100
Corresponding transverse shear in column, pounds	3700	2900	4800	5200	5800	5800
Shear due to known eccentricity of load, pounds	0	0	3000	0	1000	2000
Transverse shear in column due to nominal central load, pounds	3700	2900	1800	5200	4800	3800
Ratio of shear to compression load	.020	.016	.009	.029	.027	.021
Next highest observed values of ratio of shear to compressive load	.009 .008 .008 .007	.010 .010 .009 .009	.009 .007 .006 .006	.024 .023 .010 .008	.019 .018 .018 .018	.016 .014 .014 .011

ormation of the lattice bars as before noted, and the remainder has been tabulated under the heading "Transverse Shear in Column due to Nominal Central Load".

The failure of Column No. 1 by buckling of the lattice bars, as described elsewhere, gives further information along this line. Tests to destruction under compression had previously been made on lattice bars like those used in this column, and the results, in the absence of other data, may be useful in estimating the load carried by the lattice bars at failure. Under conditions of loading similar to the conditions in the column lattice bars, these sample bars failed under an average load of 2100 lb. Assuming that the bar in this column which first failed was carrying 2100 lb. when failure occurred, the transverse shear in the column may be computed. The following tabulated statement gives the conditions of this test, and may be regarded as supplementary to Table 6.

Column No.	Compressive Load in Pounds	Lacing	Manner of Loading	Probable Maximum Load on Lattice Bar in Pounds	Corresponding Shear in Column in Pounds	Ratio of Transverse Shear to Compression Load
1	150 000	Single 63° 30′, 1 x ¼ in. riveted	Very slight obliquity	2100	3760	0.0251

14. *Tests to Failure of Wrought-iron Columns.*—After the wrought-iron bridge posts had been tested for stress distribution under working loads, they were loaded to failure. Deformations were measured in the flange members of that part of the column on which the previous test had given the heaviest stress. Table 7 gives the result of the tests to failure. For all the tests of wrought-iron bridge posts, whether loaded centrally or eccentrically, the failures were very gradual. Final failure occurred near the middle or at the end. In the former case, high stresses in one channel had been shown by the deformation measurements at working loads. In the latter case, a bending in one channel at working loads was noted by the instruments at the panel nearest the end of the column. In two of the three columns in which failure took place in the end of the column, as the instruments did not show over-stress in the laced portion of the column, the injured ends were removed, new end connections were put on, and the columns were retested as No. 2a and 4a.

15. *Tests to Failure with Column No. 1.*—Two tests to failure were obtained with Column No. 1. In the first test, the lattice

bars failed by buckling suddenly and without warning. As tested, the column was fitted with the light lattice bars (1 x $\frac{1}{4}$ in.) riveted in place. The test had in view the trial for stress distribution under a slight obliquity, which was not carefully determined. No measuring instruments were in place. A preliminary load was being applied. When the load reached 150 000 lb. (8060 lb. per sq. in. of cross-section), the alternate lattice bars in the upper half of the column buckled. A failure of this kind was quite unexpected at such a low load. Although an observer was watching the column, the failure was so sudden that he was unable to follow the movement of the parts. In this respect it was quite in contrast to the failure of the other columns. The machine was at once stopped. Little damage was done to the column, except to the lacing bars. The webs were easily straightened, new lacing bars put on, and the column was used in another test.

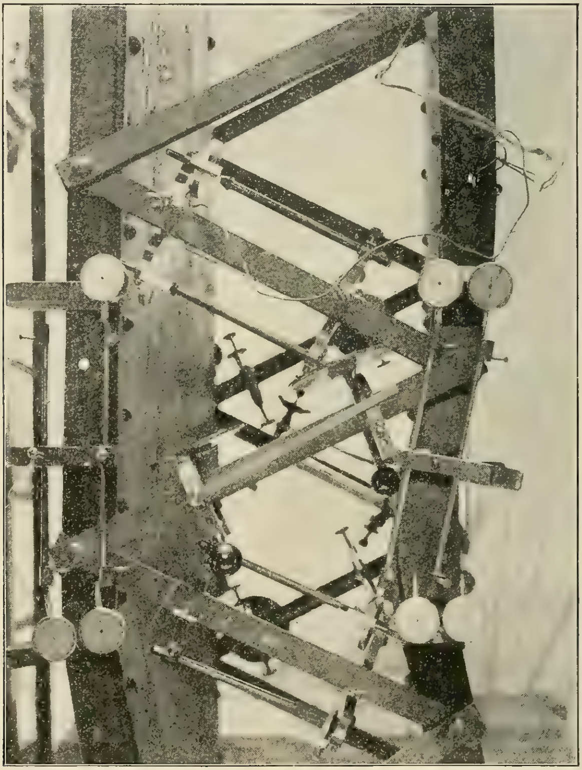

FIG. 16. COLUMN NO. 1 AFTER FAILURE.

TABLE 7.

RESULTS OF TESTS TO FAILURE.

Column No.	1	1	2	3	4	5	2a	4a
Test No.		17	6	7	8	9	13	10
Material	Steel	Steel	W. I.	W. I.	W. I.	W. I.	W I.	W. I.
Method of loading	Very slight obliquity	Central	Central	Central	Central	Central	2-in. oblique (Fig. 6)	Central
Load at failure, pounds	150 000	440 000	466 000	480 000	452 000	492 000	475 000	475 000
Average stress at failure, lb per sq. in.	8 060	23 450	26 400	27 200	25 700	27 900	26 900	26 900
Average stress at failure in tests of short pieces of flange members, lb. per sq. in.	—	—	36 800	36 800	36 800	36 800	36 800	36 800
Percentage of excess of ultimate strength of short pieces over column strength	—	—	39.5	35.5	43.5	32.0	37.0	37.0
Load at first sign of yielding, pounds	150 000	225 100	317 000	264 000	256 000	264 000	—	—
Average stress at first sign of yielding, lb. per sq. in.	8 060	12 000	18 000	15 000	14 500	15 000	—	—
Method of failure and remarks	Very sudden buckling of lacing bars in upper half	Sudden buckling of flange between adjacent lacing bars	End failed	End failed	End failed	Bowed at middle in plane perpendicular to lacing	Buckled near bottom in plane parallel to lacing	Bowed at middle in plane perpendicular to lacing

The column having been riveted up with heavier lattice bars ($1\frac{1}{4}$ x $\frac{7}{16}$ in.), it was next subjected to several tests for stress distribution and was finally loaded to failure with a central load. Measuring instruments were attached to flanges and lattice bars near that part of the column in which, from the results of previous tests, the greatest stress was expected. Fig. 16 shows the attachment of instruments to the columns. Failure occurred under a load of 440 000 lb. (23 450 lb. per sq. in. of section); it was caused by the local buckling or "wrinkling" of the north flange in panel 8, the panel in which the greatest stress had been found in Test No. 5. The failure of the column was slower than that of the preceding test in which the lattice bars buckled, but it was much more sudden than were the failures of the wrought-iron columns. One lattice bar on each side was buckled by the crippling of the channel member. The measuring instruments attached to the web at panel 8 showed from the first of the test that there was a very large stress at that point.

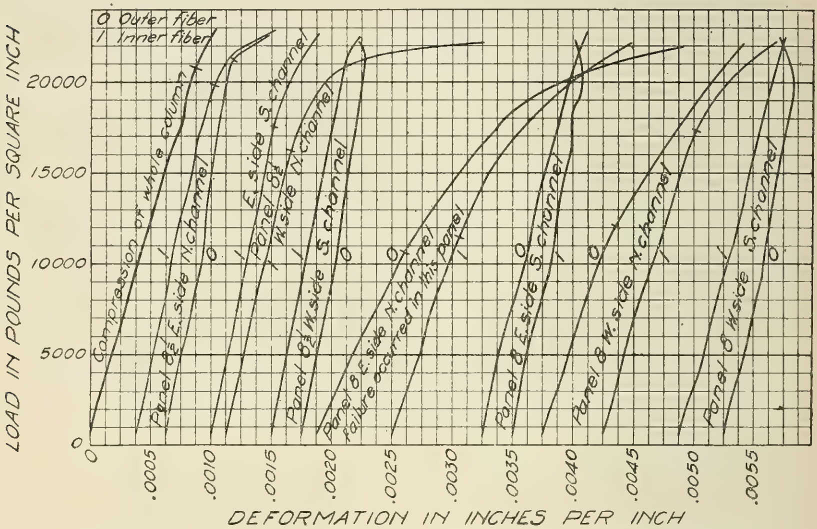

FIG. 17. LOAD-DEFORMATION CURVES OF TESTS TO FAILURE OF COLUMN NO. 1.

Fig. 17 shows the stress-deformation curve as taken at various points. The uneven distribution of stress is clearly shown, and the first sign of approaching failure is seen at about 12 000 lb. per sq. in. Fig. 16 shows the column after failure.

The low average stress at failure in Column No. 1 should be noted, and also the manner of failure. There is a sharp contrast between the gradual bowing of the stocky columns tested and the sudden wrinkling collapse of the flimsy steel column.

16. *Cross-bending Test of Columns.*—Cross-bending tests were made on one of the wrought-iron columns and on Column No. 1. The tests were made in an Olsen 200 000-lb. testing machine fitted for testing beams 20 ft. long. The columns were supported at the ends and loaded at the center with a light transverse load. The column was placed first with the plane of the lacing perpendicular to the load, and then with the plane of the lacing parallel to the load. The lattice bars used in the tests of Column No. 1 were $1\frac{1}{4}$ x $\frac{7}{16}$ in. in cross-section; in one test they were bolted in place and in another they were riveted. The deflection at various points along the beam was measured with Ames test gauges, and the actual curve assumed by the column under transverse load

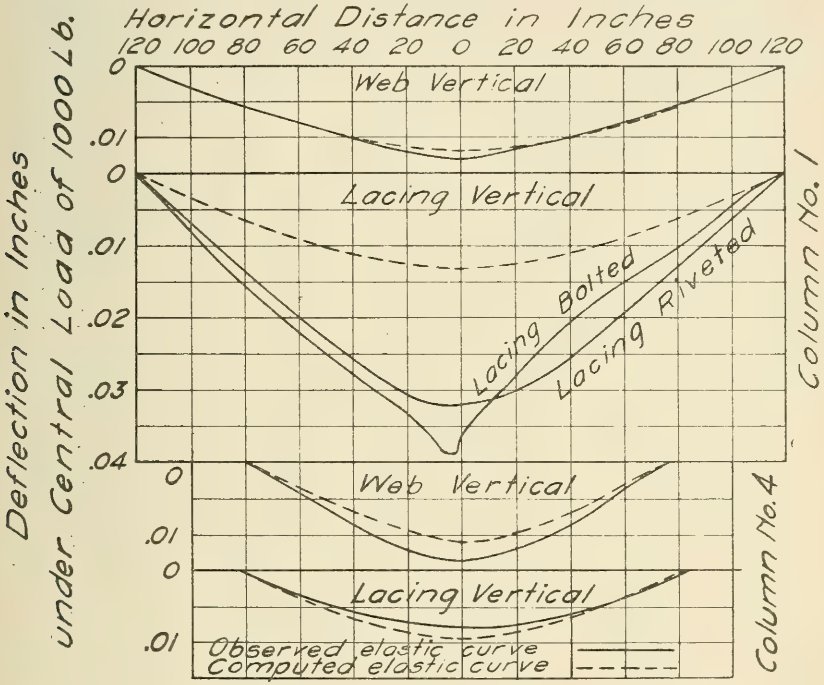

FIG. 18. DEFLECTION OF COLUMNS UNDER CROSS BENDING.

was thus determined. The theoretical elastic curve was computed from the common theory of flexure, not counting the lattice bars in the calculation of the moment of inertia. Fig. 6 (p. 13) shows the deflectometers and extensometers on Column No. 1 under the cross-bending test. Fig. 18 shows the deflection curves given by the columns under transverse load and also the computed elastic curves.

It will be noted that when tested with the lacing vertical, Column No. 1 shows much greater deflection than that computed from the usual beam formula, while the stiffer wrought-iron column shows a much closer agreement with the curve, the heavy lacing apparently adding stiffness.

III. FIELD TESTS OF COLUMNS.

17. *Description of Bridge.*—The field tests of columns were made on compression members in a bridge which spans the Sangamon river near White Heath, Illinois, on the line of the Illinois Central Railroad between Champaign and Clinton, Illinois. This bridge is an eight-panel, single-track, Pratt truss, having a span of 158 ft. 6 in. Fig. 19 gives a diagram of the bridge, and the frontispiece is from a photograph of the bridge under test.

18. *Members Investigated.*—The members in which stresses were measured were Post U_2L_2 South, U_3L_3 South, U_3L_3 North,

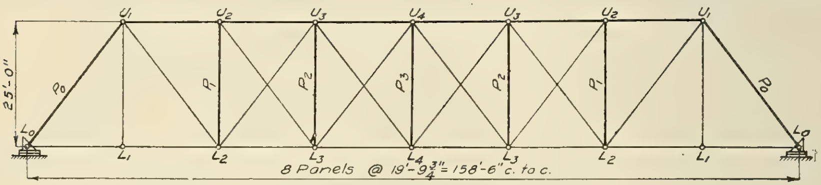

FIG 19. DIAGRAM OF WHITE HEATH BRIDGE.

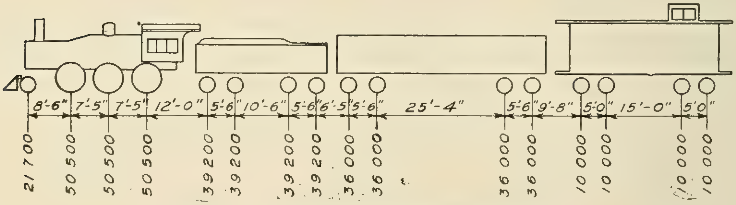

FIG. 20 DIAGRAM OF TEST TRAIN.

and Upper Chord U_3U_4 South. The location of these members is shown in the bridge diagram, Fig. 19. The upper chord was made up of two built-up channels with a cover plate on top and double lacing across the bottom. The end of each upper chord was riveted to a connection plate to which was riveted the adjacent end of the next upper chord and also the post under the junction of the chords. The posts were made up of two steel channels double laced, and the floor beams were directly riveted to the posts. The upper ends were riveted to a connection plate as noted above and the lower ends carried pins to which the lower chord members (eyebars) were attached. Fig. 21 shows in detail a post and upper chord.

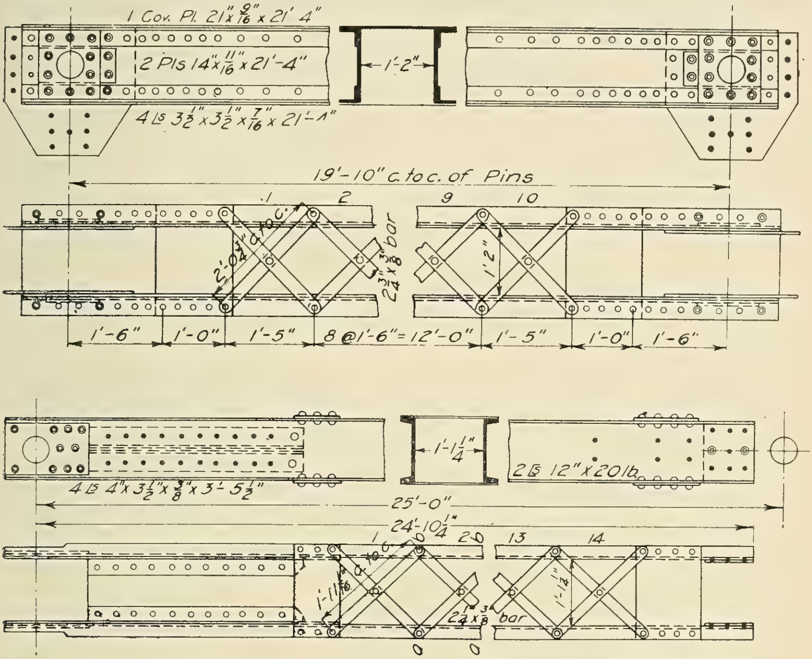

Fig. 21. Upper Chord and Post of White Heath Bridge.

19. *Application of Load.*—The test load applied to the bridge consisted of a mogul locomotive and tender, I. C. R. R. No. 555, followed by a loaded coal car and a caboose. Fig. 20 shows the test train, with dimensions and weights. This train was furnished through the courtesy of the railroad company.

20. *Measurement of Deformation.*—Ames test gauges were used as extensometers, and the method of attachment was the same as in the laboratory tests of columns. The method of reduction of instrument readings to stresses at the extreme fibers of members was also the same.

TABLE 8.

STRESSES IN POSTS OF WHITE HEATH BRIDGE.

Panel	NORTH CHANNEL						SOUTH CHANNEL					
	East Side			West Side			East Side			West Side		
	Outer Fiber	Center of Gravity	Inner Fiber	Outer Fiber	Center of Gravity	Inner Fiber	Outer Fiber	Center of Gravity	Inner Fiber	Outer Fiber	Center of Gravity	Inner Fiber
POST U_3L_3 SOUTH.												
1*	5 000	5 300	5 400	2 600	2 700	2 700	4 900	5 000	5 000	2 300	2 500	2 600
2	3 400	3 500	3 500	1 900	1 600	1 500	3 300	3 400	3 400	1 600	1 800	1 800
3	3 500	3 800	4 000	1 800	1 900	2 000	2 600	2 900	3 100	2 600	2 200	2 100
4	3 700	3 400	3 300	2 800	3 000	3 000	1 600	3 100	3 600	2 400	2 800	2 900
5	3 500	3 900	4 000	2 900	2 900	2 900	2 800	3 000	3 100	2 200	2 600	2 800
6	3 600	3 600	3 600	3 400	3 800	3 900	3 400	3 400	3 400	4 100	3 400	3 200
7	2 600	3 200	3 400	3 300	3 100	3 000	2 400	3 000	3 300	2 600	2 700	2 800
8	3 300	3 200	3 200	3 900	3 600	3 500	3 600	3 400	3 300	3 700	3 900	3 900
9	3 200	3 100	3 000	3 600	3 300	3 200	1 700	2 500	2 800	2 900	3 300	3 400
10	2 800	2 700	2 700	3 100	3 300	3 300	2 700	2 400	2 300	3 300	3 700	3 900
11	3 300	2 900	2 800	4 500	3 400	3 100	2 900	2 000	1 700	3 500	3 900	4 100
12	1 400	2 000	2 300	3 100	3 200	3 200	1 800	1 800	1 800	4 800	4 700	4 600
13	1 300	1 500	1 500	2 800	2 700	2 600	2 600	2 900	3 100	5 200	4 900	4 800
POST U_3L_3 NORTH.												
1	4 900	4 900	4 900	2 600	2 500	2 500	4 800	4 900	4 900	2 100	2 700	2 800
1½	4 800	4 700	4 700	2 900	2 800	2 700	3 100	4 900	5 700	900	1 500	1 700
2	4 800	4 400	4 300	2 600	2 500	2 500	4 900	4 700	4 600	2 700	1 700	1 300
2½	4 000	3 900	3 900	2 700	2 800	2 900	4 300	3 700	3 500	2 300	1 800	1 600
3	3 900	4 200	4 300	2 800	2 900	2 900	......	......	......	......	......	......
3½	3 900	3 900	4 000	2 400	2 500	2 500	3 200	3 800	4 100	2 400	2 500	2 500
4	3 400	4 600	5 000	2 700	2 700	2 700	3 900	3 700	3 700	3 500	3 200	3 100
4½	3 800	3 400	3 200	2 500	2 300	2 200	3 500	3 500	3 400	3 100	3 000	3 000
5	3 900	3 700	3 600	3 700	3 700	3 700	3 100	3 600	3 800	1 400	2 100	2 400
5½	4 100	3 600	3 400	4 000	3 400	3 200	3 500	3 900	4 100	3 500	2 900	2 800
6	3 600	3 200	3 100	3 400	3 300	3 200	3 700	3 500	3 400	3 900	3 600	3 500
6½	3 300	3 300	3 300	3 600	3 500	3 500	4 500	4 700	4 800	2 000	2 400	2 600

*No explanation for the high values in Panel 1 has been found. Five determinations of stress were made, including the removal and re-attachment of instruments.

21. *Routine of Tests.*—As in the laboratory tests, the stress distribution in the channels and the lattice bars was studied. The method of procedure was as follows. Instruments were placed on some portion of the column to measure the deformation over a short gauge length, and a reading was taken. The test train was then run upon the bridge to a given position (one approxi-

mating the maximum load on the member under test), and the instruments were read again. The train was then run off the bridge, and the instruments were again read. This procedure was repeated several times, at least three applications of the load being made and frequently several more. The instruments were then moved to another part of the column, and that part was tested. Observations were made on both flange members and lattice bars. The tests covered a period of eight days. The weather was ideal with the exception of one day.

TABLE 9.

STRESSES IN UPPER CHORD OF WHITE HEATH BRIDGE.

Stresses are given in lb. per sq. in.

Panel	LOWER SIDE (LACED).				UPPER SIDE (COVER-PLATE)				
	NORTH CHANNEL		SOUTH CHANNEL		Distance from End inches	North Edge	Over North Web Plate	Over South Web Plate	South Edge
	Outer Fiber	Inner Fiber	Outer Fiber	Inner Fiber					
1	4 300	3 900	5 000	5 500	33	5 500	6 000	5 200	5 700
2	4 900	4 300	4 500	4 800	57	....	....	5 200	5 500
3	2 800	5 500	3 400	4 500	81	5 200	5 400	5 900	5 300
4	2 800	5 100	4 200	5 300	105	5 000	6 100	5 700	6 000
5	5 700	5 400	3 900	4 800	129	4 800	5 900	5 900	5 900
6	5 500	4 800	5 100	4 200	153	5 400	5 700	5 500	5 600
7	5 900	4 700	3 400	3 600	177	5 000	5 000	5 700	5 600
8	6 200	5 300	3 300	4 400	....	....	....	....	....
9	6 000	5 300	4 700	3 800	....	....	....	....	....
10	5 900	5 100	4 400	4 900	....	....	....	....	....

22. *Results of Tests for Stress Distribution in Channels.*—Table 8 gives the results of the tests to determine the stress distribution and variation in the channels of the bridge posts, and Table 9 gives those for the top chord. The stresses given were calculated from the observed deformations, using a modulus of elasticity of 30 000 000 lb. per sq. in. The conditions of measurement of deformation were much the same as in the laboratory tests. The stress noted is the average stress over a space of 4½ in. on either side of the point indicated.

Fig. 22 and 23 show graphically the stress distribution and variations. In these figures the full lines give the stresses at the west side (front), and the dotted lines the stresses at the east side (back).

In Table 10 (p. 44) are given a number of the highest observed fiber stresses. The excess of the maximum fiber stress is given

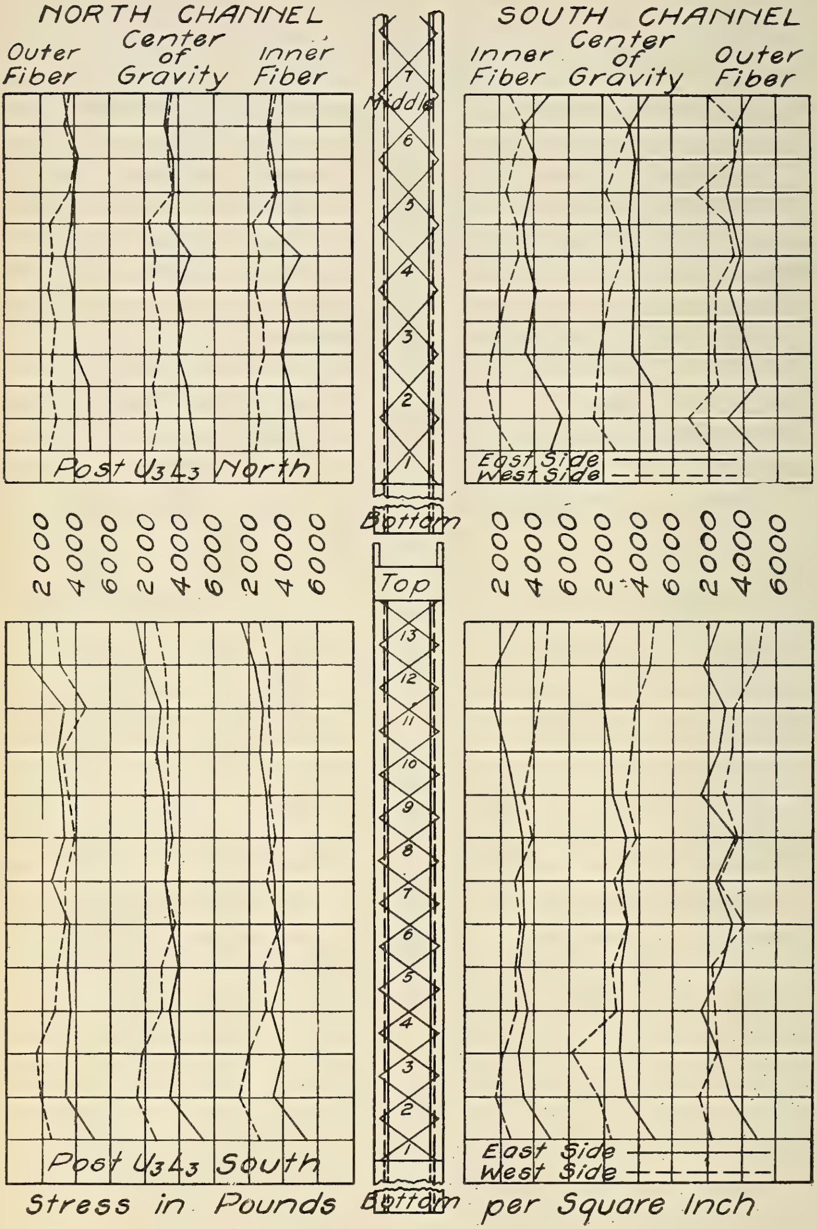

FIG. 22. STRESS DISTRIBUTION IN POST U_3L_3 NORTH AND U_3L_3 SOUTH OF WHITE HEATH BRIDGE.

as a percentage of the average stress. At most sections the maximum stress was in the outer fiber of the channel, but in some cases it was found at the inner fiber.

In the tests of the bridge posts an attempt was made to determine the stresses in a few of the lattice bars. These stresses were very small, and the precision of the extensometer was not sufficient to measure them with any great degree of accuracy.

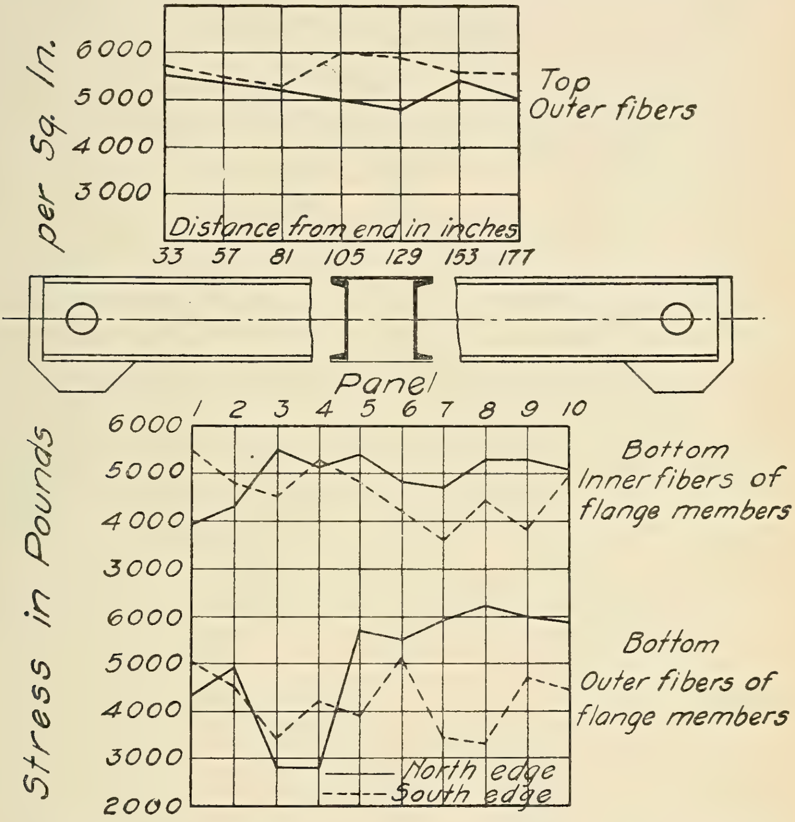

FIG. 23. STRESS DISTRIBUTION IN UPPER CHORD U_3U_4 OF WHITE HEATH BRIDGE.

It should be noted that the lacing of the posts in this bridge was double, and the bars were riveted together at their intersection. In several cases it was found that a lattice bar under load bent in the shape of a very flat S-curve, the point of attachment to another lacing bar, at the middle, being a point of inflection.

23. *Special Tests on Bridge Columns.*—Tests were made on the batten plates at the top of one of the posts, and under load a slight bending of the plates between channels was found. The bending took place in a horizontal plane.

TABLE 10.

MAXIMUM OBSERVED FIBER STRESS IN FLANGE MEMBERS OF COLUMNS IN WHITE HEATH BRIDGE.

Column number...........	$U_3 L_3$ South	$U_3 L_3$ North	$U_3 U_4$ South
Test number......	F 1	F 2	F 3
Lacing.....................	Double 45° riveted at crossing	Double 45° riveted at crossing	Cover plate on top. Double 45° on bottom
Maximum observed compressive stress in an extreme fiber, lb. per sq. in.	5200	5700	6200
Excess maximum observed stress over average, per cent. Highest five values......	73* 63 60 57 47	64 48 41 31 31	20 19 17 17 17

* No values from Panel 1 have been included in this table as no explanation is known of the high stresses indicated in that panel.

In one post the change of stress was observed as the locomotive and train moved across the bridge. Extensometers were placed at aa, bb (Fig. 21), and on the floor beams, and the changes in reading were noted as the train moved across the bridge. In the inner channel of the post, tension was set up as the locomotive came opposite the post. The maximum amount of tension observed in the inner channel when the locomotive was opposite the post was about three-quarters of the compression in the outer channel.

IV. TESTS OF LATTICE BARS, SMALL COLUMNS, AND COLUMN MATERIAL.

24. *Compression Tests of Lattice Bars.*—Many of the lattice bars in a column, as they transmit stress from one flange member of the column to the other, are under compression. To study the action of lattice bars under compression, a series of tests on single lattice bars was made. Fig. 24 shows the arrangement of the apparatus. The lattice bar was tightly bolted to the blocks, B_1 and B_2. The upper block, B_1, was fastened to the cross-head of a testing machine, and the block B_2 was pressed against the

weighing table of the testing machine. A spherical-seated bearing block was used, to insure an even bearing. Ames test gauges, E, mounted on suitable frames, were attached to the lattice bar over a short gauged length. From the readings of these gauges, the deformation of the extreme fiber of the bar was computed.

In this test of lattice bars, the load was applied with an eccentricity approaching that to be expected in a column for the lattice bars which are next to the flange member (here designated "under" bars). The lattice bars outside of these "under" bars are here designated "over" bars. The stress distribution across the section of the "over" bars, which are under compression, is probably more uneven than the stress distribution found in these tests. However, these tests give some idea of the relative behavior of lattice bars of various proportions, and of the large eccentricity of loading of all lattice bars.

Lattice bars of the following cross-sections were tested: Flat bars $1\frac{1}{2}$ x $\frac{1}{4}$ in., 1 x $\frac{3}{8}$ in., $\frac{7}{8}$ x $\frac{7}{16}$ in.; angles $1\frac{1}{2}$ x $1\frac{1}{2}$ x $\frac{1}{8}$ in.; channels $1\frac{1}{2}$ x $\frac{3}{4}$ x $\frac{1}{8}$ in. Several channel and angle lattice bars were tested with ends flattened and ribs turned inward, to minimize the eccentricity of loading. Bars of the following lengths between centers of rivet holes were tested: $8\frac{1}{2}$ in., $13\frac{1}{2}$ in., and 20 in. The rivet holes were $\frac{1}{2}$ in. in diameter. All bars were tested in a Philadelphia Machine Tool Company's 100 000-lb. testing machine, and loads and extensometer readings were taken to failure.

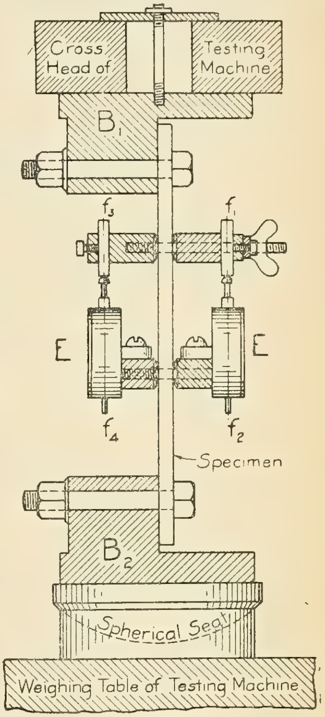

FIG. 24. ARRANGEMENT OF APPARATUS IN COMPRESSION TESTS OF LATTICE BARS.

Observations were also made on the behavior of a lattice bar in a column under load, with a view to determine the distribution of stress over the section. For this purpose Column No. 1 was loaded obliquely. The instruments were placed on an "over" bar which had been found to carry a high compressive stress, and readings were taken to determine the distribution of stress across the section.

When Column No. 1 was under cross-bending test, observations were made to determine the stresses transmitted by lattice bars and their distribution over the section of the bars. Extensometers were placed successively on most bars under compression on one-half of the column, and on some bars which were under tension. In both of these tests the bars were $1\frac{1}{4}$ x $\frac{7}{16}$ in., and were riveted.

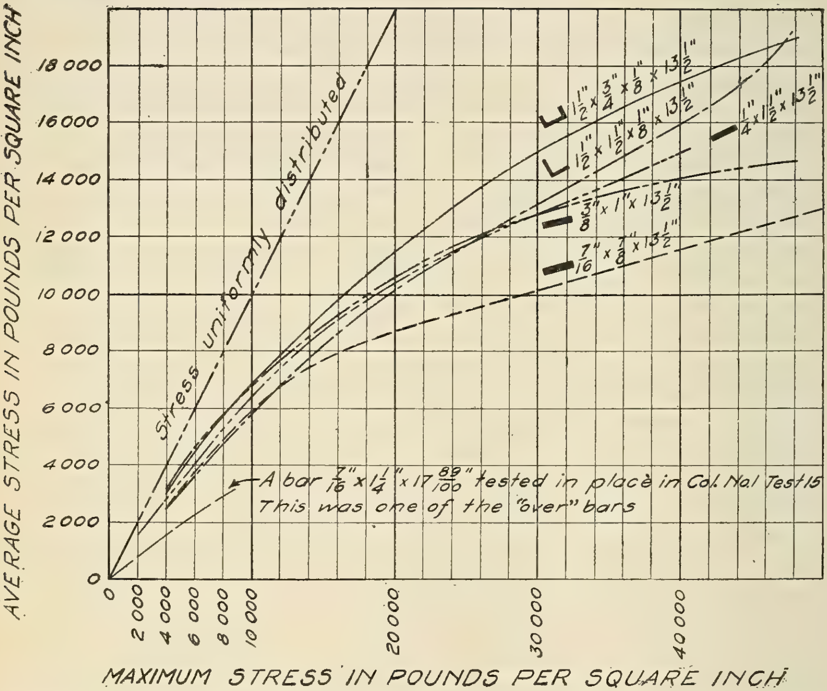

FIG. 25. FIBER STRESS IN COMPRESSION TESTS OF LATTICE BARS, ENDS HELD AS IN FIG. 24.

25. *Results of Tests of Lattice Bars.*—The results of the tests of single lattice bars are given in Fig. 25 and 26, and in Tables 11 and 12. Fig. 25 shows the ratio of maximum to average stress in the bars $13\frac{1}{2}$ in. long between centers of rivet holes. It also gives the result of the test of stress distribution in a lattice bar of Column No. 1. Table 11 gives the stresses at failure of the various bars tested singly. The average stress on the various

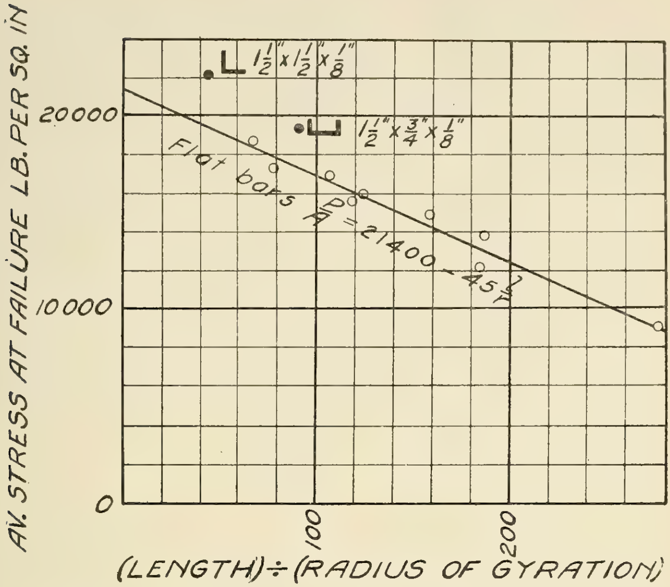

FIG. 26. RESULTS OF COMPRESSION TESTS TO FAILURE OF LATTICE BARS.

TABLE 11.

COMPRESSION TESTS OF LATTICE BARS.

Average of two specimens.

Section of Bar inches	Distance c. to c. of Rivet Holes inches	$\frac{l}{r}$	Stress at Failur lb. per sq. in.	Stress at Failure for Steel of 40 000 lb. per sq. in. Yield Point* lb. per sq. in.
1½ x ¼ flat	20	277	9 900	8 900
1 x ⅜ flat	20	184	12 900	12 200
⅞ x 7/16 flat	20	158	14 500	15 000
1½ x ¾ x ⅛ channel	20	90	20 800	19 400
1½ x 1½ x ⅛ angle	20	43	22 600	20 100
1½ x ¼ flat	13½	187	15 400	13 800
⅞ x 7/16 flat	13½	107	16 300	16 800
1 x ⅜ flat	13½	124	16 900	15 900
1½ x ¾ x ⅛ channel	13½	61	bolt sheared	....
1½ x 1½ x ⅛ angle	13½	29	bolt sheared	......
1½ x ¼ flat	8½	118	17 300	15 500
⅞ x 7/16 flat	8½	67	18 100	18 700
1 x ⅜ flat	8½	78	18 300	17 200
1½ x ¾ x ⅛ channel	8½	38	bolt sheared	......
1½ x 1½ x ⅛ angle	8½	18	bolt sheared	......

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*The values in this column were obtained by multiplying the observed stress at failure by $\left(\frac{40\ 000}{\text{yield point determined from tests}}\right)$.

bars, which gave a maximum fiber stress of 40 000 lb. per sq. in., as taken from these tests, has been noted and is given in Table 12. The results of the tests to failure are shown graphically in

TABLE 12.

AVERAGE STRESS IN LATTICE BARS WHICH CORRESPONDS TO A MAXIMUM FIBER STRESS OF 40 000 LB. PER SQ. IN.

Section of Bar inches	Distance c. to c. of Rivet Holes inches	Corresponding Average Stress lb. per sq. in.
7/8 x 7/16 flat	13½	11 600
1 x 3/8 flat	13½	14 000
1½ x ¼ flat	13½	14 900
1½ x 1½ x 1/8 angle	13½	15 900
1½ x ¾ x 1/8 channel	13½	17 500

TABLE 13.

STRESS IN LATTICE BARS OF COLUMN NO. 1 UNDER CROSS BENDING.

Column tested as a beam centrally loaded over span of 19 ft. 8 in.; lacing bars $1\frac{1}{4}$ x $\frac{7}{16}$ in.; 17.89 inches c. to c. of rivet holes; rivets $\frac{1}{2}$-in. in diameter.

Bar	Maximum Fiber Stress from Ames Dials	Average Stress from Ewing Extensometer	Ratio Maximum to Average
	"Over" bars in compression		
14 E	6000	2600	2.31
16 E	8300	2000	4.15
18 E	4300	1800	2.39
20 E	7700	1400	5.50
22 E	7000	2900	2.42
24 E	8900	2200	4.04
			Av. 3.47
	"Under" bars		
15 W	4300 c*	2500 c	1.72
25 E	3800 t*	3100 t	1.23
17 E	3900 t	3000 t	1.30
25 W	3900 c	2800 c	1.39
19 W	4500 c	2900 c	1.55
			Av. 1.44
	"Over" bars in tension.		
16 W	7000	3000	2.33
18 W	7000	2200	3.19
20 W	4500	2400	1.87
22 W	5700	2200	2.59
24 W	7000	2700	2.59
26 W	3800	2200	1.73
			Av. 2.38

* c, bar in compression; t, bar in tension.

Fig. 26. The angle and channel bars tested with flattened ends failed in the flattened part at loads no greater than similar bars not flattened at the ends.

Table 13 gives the results of the test for stress distribution in the lattice bars of Column No. 1 as it was stressed in cross bending.

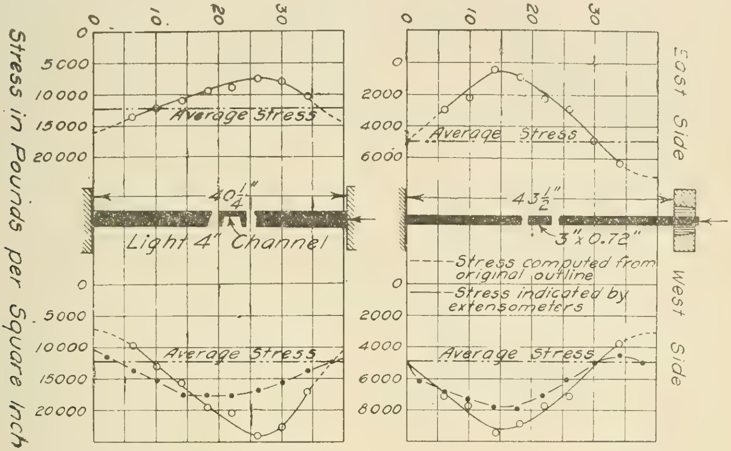

FIG. 27. STRESS DISTRIBUTION IN SMALL COLUMNS.

26. *Tests of Two Small Compression Pieces.*—Tests of two small compression pieces were made in order to study the effect of slight bends and kinks in the column upon the distribution of stress. The deviation from a straight line, in these nominally straight pieces, was measured before the load was applied. The deformations on two opposite faces for a given load were measured. The extensometer was similar to that used on the single lattice bar tests. The instrument was shifted from one position to another along the column. The columns were finally loaded to failure. One of the columns was a flat piece of steel, 3 x 0.72 in. in cross-section, and 46 in. long. It was held at the upper end by wedge grips in the cross-head of the machine and at its lower end rested on a spherical-seated block. The second compression piece was a 4-in. channel 40 in. long. The ends were planed square; the upper end bore on a flat compression plate in the iron head of the machine, and the lower end rested on a spherical-seated block.

TABLE 14.

TENSION TESTS OF MATERIAL FROM COLUMNS.

Test Piece from	Material	Number of Test Pieces	Average Stress at Yield Point, lb. per sq. in.	Average Stress at Ultimate, lb. per sq. in.	Elongation in 2 inches, per cent
Col. No. 1 Angles	Steel	2	43 300	61 600	37
$\frac{7}{16}$ x 1¼ lacing bar	Steel	2	40 700	58 100	42
1 x ¼ lacing bar	Steel	1	42 400	62 000	38
Channels of wrought-iron columns	Wrought-iron	3	30 700	46 800	17

TABLE 15.

TENSION TESTS OF LATTICE BARS.

Shape	Dimensions of Cross-section of Whole Bar inches	Number of Specimens Tested	AverageStress at Yield Point, lb. per sq. in.	AverageStress at Ultimate, lb. per sq. in	Elongation in 2 inches per cent
Channel........	1½ x ¾ x ⅛	1	43 000	57 600	36.5
Angle...........	1½ x 1½ x ⅛	2	45 000	59 300	24.5
Flat............	⅞ x $\frac{7}{16}$	2	38 700	57 000	45.5
Flat............	1 x ⅜	2	42 400	61 700	45.8
Flat.......	1½ x ¼	2	44 600	60 800	42.8

Fig. 27 gives the results of tests of the small columns. The dotted line represents the maximum fiber stress computed by considering the eccentricity of loading at any cross-section to be equal to the deviation of that section from a straight line connecting the ends of the column. The deflections were slight, and were neglected in the calculations. The solid line represents the stresses on the two sides of the column, as determined from the extensometer readings.

27. *Tests of Column Material.*—Table 14 gives the results of the tensile tests of samples of materials from various parts of the flange members of the columns, and also of tension tests of lattice bars. Table 15 gives tension tests of lattice bars like those used in the compression tests of lattice bars.

V. Discussion.

28. *The Action of Built-up Compression Pieces.*—In analytical discussions of column action, the stress is usually assumed to vary uniformly from a minimum on one side of the cross-section to a maximum on the opposite side, and the whole cross-section of the column is considered to act as a unit. The longitudinal axis of the column is also considered to take a definite elastic curve under load. In the derivation of most column formulas, it is assumed that the amount of deflection of the elastic curve from the original position of the axis is an important element in fixing the maximum stress in the column. Although these assumptions are generally used as the basis of column formulas, it may be well to consider whether conditions may not exist, in columns of ordinary form and dimensions, which will render doubtful the general applicability of some of these assumptions and will dwarf the effect of others. At any rate, it seems worth while to consider the effect of other conditions in a built-up member. It must be borne in mind that the built-up column is subject to imperfections of fabrication, and that some crookedness and eccentricity must exist. The component parts of the column may be relatively slender and flimsy. Whether there is integrity of cross-section under load, is a question. In the tests herein described, the amount of deflection from the original axis, for loads up to a point somewhat below incipient failure, was found to be slight (generally between 0.04 and 0.1 in.), much smaller than necessary to account for the stresses observed in the columns.

The action of short columns at failure may be expected to be different from that of longer columns, although the stresses up to incipient failure may be the same. Granting that the conditions of non-straightness are such that the distribution of stress over the cross-section is the same for the two lengths of columns, and that the deflection of the column is so slight as not to affect materially the stresses developed, the longer column will be in more danger of immediate and sudden collapse after the yield point of the material in any fiber has been reached, and the total load carried before complete failure will, in general, be less. This is because, in a ductile material, after the stress at one side of the column has passed the yield point, the total resistance of the section to compression will increase, while the resistance to cross bending may not. Under the conditions named, the bending moment due to eccentricity will be the same until the yield point in some fiber is reached. After yielding begins, the greater deflection in the longer column rapidly increases its relative eccentricity, and more rapid failure may be expected than with the shorter column.

29. *Indications of Data.*—It will aid in the interpretation of the data of the distribution of stress over the channel members of the columns to point out a few simple indications. Reference may be made to the diagrams in Fig. 8 to 15, and Tables 2, 3, 8, and 9.

1. Any lack of agreement between the average load stress and the average of the stress given for the four centers of gravity of channel flanges may be ascribed to errors of observation.

2. If the stress at the center of gravity of one channel is above the average stress throughout the length of the column, and the corresponding stress for the other channel is similarly below the average stress, there must be an eccentricity in the application of the load at the two ends. If the stresses at the center of gravity of one channel member form in the diagram a straight line which crosses the line of average stress, and that for the other channel crosses in the opposite way, the eccentricity of the load application must be oblique.

3. If the stress at the center of gravity of a channel in near-by points is greater first in one channel and then in the other, the change may be due to crookedness of the column throughout that part of the length.

4. If, in one channel or in one channel flange, the stress at the center of gravity remains constant and that of the extreme fiber varies, the change may be due to local crookedness of this channel and there will be a lateral bending of this member.

5. If the front side of a channel has a higher stress than the back side, there must be bending action through its web, and *vice versa.*

6. Changing stresses in the diagonally opposite corners of a channel may indicate twisting of the channel, and another combination of stresses may indicate a twisting or oblique distortion of the column as a whole.

An inspection of the diagrams shows that all these indications are found in the tests.

7. To be in accord with the principles of column formulas of the Rankine type, there should be from end of column to middle a regular increase in the stress in one channel or in one flange of a channel and a corresponding decrease in the stress in the other. Verification by an agreement between the distribution of stress and the theory would be important. It will be seen that this verification was not obtained.

30. *Does the Built-up Column Act as a Unit ?*—Engineers have often expressed doubt as to whether the parts of a built-up column act as a unit, although column formulas assume this unity of action. The tests throw some light on the question of the integrity of cross-section under load. The individual channel, of course, acts as a unit to resist bending action, though there are indications of twisting. The integrity of the whole section with reference to a plane parallel to the lacing seems probable, except as twisting action exists. With reference to a plane through the axis perpendicular to the plane of the lacing, this unity of action is not so certain. The tests on the distribution of compressive stress and likewise the cross-bending tests of the columns indicate that these built-up columns did not in all cases act as a unit but rather as two members not fully restrained by the lacing. The stresses in two channels as points in the same cross-section do not give the regularity of variation which would exist if the column bent as a unit. The elastic curve assumed by Column No. 1 under cross-bending load, shown in Fig. 18, differs from the computed elastic curve, though that for the wrought-iron column gives little difference. In the case of the posts of the White Heath bridge, however, there is much closer agreement and a seemingly closer approach to unity of action.

31. *Effect of Non-straightness of Built-up Columns Upon Distribution of Compressive Stress.*—The effect of crookedness or other irregularities of a constituent member of a built-up column may be realized if a rough analysis of the case be made. Consider a part of one of the channels forming a column, taking the length between the connections of two adjacent lattice bars. This member is under compression. Owing to non-straightness or to the non-homogeneity of the material, the load on this short piece is not evenly distributed over the section; that is, it is not centrally loaded, but may be considered to have an eccentricity with respect

to the gravity axis. Call this eccentricity e (Fig. 28). Neglect any deflection of the piece under consideration due to the load. Call the compression load coming on this piece P; A its area of cross-section; I its moment of inertia about YY, and r the corresponding radius of gyration; and c the distance from YY to the remotest fiber. Then the bending moment due to the eccentricity is Pe. The maximum stress will be

$$f = \frac{P}{A} + Pe\frac{c}{I} = \frac{P}{A}\left(1 + \frac{ec}{r^2}\right).$$

The excess of the stress in the extreme fiber of the piece over the average stress, produced by the eccentricity e is then $\frac{P}{A}\frac{ec}{r^2}$, and hence the term, $\frac{ec}{r^2}$, gives the proportionate excess of stress in the extreme fiber. This value is applicable to the channel, or to one flange of the channel, or it may be applied to the column as a whole by using the properties of the whole section. In the single channel under consideration, c is relatively large and r is relatively small, and the excess of maximum stress for a given eccentricity e may be expected to be relatively large. It will be seen that for an excess of 50% in the extreme fiber of a channel of Column No. 1, e, by this formula, would be 0.045 in., and, in the wrought-iron columns, 0.057 in. A slight variation from straightness in a channel will account for considerable increase of stress.

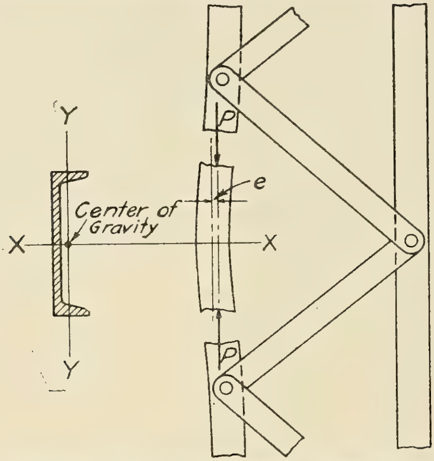

FIG. 28. EFFECT OF ECCENTRICITY IN CHANNEL MEMBERS.

32. *Excess of Maximum Fiber Stress over Average Stress in Channel Members.*—The diagrams and data show that the compressive stress is unevenly distributed over the cross-section of the columns tested, and also that there is great variation in this distribution at various sections along the length of the column. It will be noted that in a number of sections the excess of stress was from 40 to 50 per cent. In one test of Column No. 1, an excess of 67 per cent was found, and in the White Heath bridge an excess of 73 per cent. Possibly these values were unusual or the observations were erratic, but the indications of a fiber stress of from 40 to 50 per cent in excess of the average stress were not uncommon.

It may be seen that among the causes to which the high fiber stress may be attributed are (a) non-straightness of the column as a whole, (b) non-straightness of the component channels, or eccentricity in the delivery of stress to them by the lacing, and (c) unknown eccentricity in the application of the load. It would be of interest to know how much of the increase of stress may be due to any one of these conditions. A study of the tests of Column No. 1 shows that generally only a small amount may be said to be due to non-straightness of the column as a whole. In but few cases is it found to be more than, say, 5 per cent; in four places it seems that the excess attributable to this may be estimated to be between 20 and 25 per cent. The effect of non-straightness of the individual channels seems to be greater. At several points the excess of stress attributable to this cause appears to be from 30 to 50 per cent. As already noted, a kink in the channels of 0.045 in. would give, by the analysis made, an eccentricity sufficient for a 50% increase in stress. Not all of this crookedness need be between adjacent rivet points, as the stress may not become normal for some distance on either side. The effect of the third condition, eccentricity of application of the load, will vary with the construction. In Column No. 1 the effect of undetermined eccentricity of application of load appears to be not nearly as great as the effect of non-straightness of the component channels.

In the wrought-iron columns, which are much stockier, the lack of straightness in individual channels has less effect, seemingly less than 15 per cent, and much the larger part of the high fiber stresses appears to be due to general column eccentricity or to eccentricity of loading.

The results for the posts of the White Heath bridge are of interest in this respect. It is evident that the effect of non-straightness of channels was not large, and also that the effect of non-straightness in the column as a whole was relatively small. There is, however, an evident bending in the direction of the web of the channels. For example, in U_3L_3 South, the back side of the channels has the maximum stress at the top and the front side at the bottom. The bending moment producing this may be due to obliquity of end pressures or to a bending by the connecting floor-beam and top cord. A twisting action is also apparent. Posts U_3L_3 North gave quite similar results.

33. *Effect of Cover-plates and End Connections.*—In the tests of the White Heath bridge, the effect of the cover-plate seems striking. The upper chord, U_3U_4, composed of two built-up channels with one cover-plate, gave an excess fiber stress of 20 per cent at the worst section, while the post, composed of two channels laced on both sides, gave a maximum of 73 per cent. The high value in the posts may be due to other causes, but it seems reasonable to expect that the cover-plate will act to reduce the irregularities in fabrication. Engineers have stated that columns having a cover plate are fitted into their places during erection with less labor than is required for columns with lacing on both sides. Tests on the stress distribution of such columns would be valuable as affording a basis of definite comparison.

The connections of the ends of posts evidently exerted a very noticeable effect on the stress distribution. In one of the posts tested, the stress was greatest at one corner of the post at the top and at the diagonally opposite corner at the bottom. It will be remembered that the posts were riveted to the top chord, and were connected with the lower chords by pins. The floor-beams were riveted to the sides of the posts, and this connection affects the stress distribution. Readings of deformations taken on the floor-beams and posts show that the loaded beam was partly restrained at the ends by the post, though this restraint introduced a bending moment at the end of the post only about one-quarter as great as at the center, and that there was an appreciable bending in the post.

34. *Stresses in Column Lacing.*—If the load carried by one channel of a column was the same throughout its length, no stress would be carried by the lattice bars. Such stress is developed

whenever there is a change in the relative amount of loads carried by the two channels. If, at the section AB (Fig. 2, p. 11), there is an equal division of load between the two channels, and also at the section CD, and if at some section EF, the division of load is unequal, it is evident that the lattice bars must be called into action to transmit this stress, and that transverse shear exists in the interval. In general, the conditions producing this will be complex, rendering analysis unsatisfactory, except in so far as the shear may be due to a known eccentricity of loading.

It is evident from the tests that the relative stress in the two channel members varies considerably from end to end and that the stress in the lattice bars also varies. It seems probable that the transverse shear developed may be traced largely to irregularities in outline, or at least that these irregularities may be expected to cover up other causes of stress in the lacing of centrally-loaded columns, if we include in such irregularities all unknown eccentricity. The futility of attempting to determine analytically the stresses in column lacing, using as a basis either a bending moment curve which varies regularly from end to middle or an assumed deflection curve, is apparent from a study of the variation of stress in the columns of the tests and in that of the lattice bars.

The amount of transverse shear necessary to produce the maximum observed lattice-bar stress (given in Table 6) is of interest, though of course it cannot be taken to be conclusive. The measurements were generally made at working loads. So far as observations were made on columns tested to failure, the distribution of stress remained much the same up to incipient failure. The values given in Table 6 indicate maximum average stresses in the bars such as would be caused by a transverse load ranging from 2% to 6% of the central compression load or of a transverse shear of 1% to 3% of the load.

35. *Compressive Strength of Lattice Bars*—In the discussion of stress developed in column lacing, the stress considered was the average over the bar. As usually attached, there is considerable flexure in the bar, and the ability of the bar to carry this eccentric load should be considered. The bars are most likely to fail in compression, since they act as long columns eccentrically loaded. This compressive strength may be greatly diminished by the bending which they frequently receive in transportation and erection.

The tests of individual lattice bars (Fig. 25 and Table 12) show that the maximum fiber stress may be several times the average stress. It is also seen that even in a short lacing bar the maximum load carried is only about one-half the yield point of the material. The necessity of using very low working loads on lattice bars appears to be important. It will be noted that at low stresses there is similarity of distribution of stress in the slender bars and in the thicker bars, but the slender bars fail at smaller computed fiber stress.

The results of tests to destruction of individual lattice bars (flats) are fairly well represented by the formula:

$$\frac{P}{A} = 21\,400 - 45\frac{l}{r}$$

where $P =$ load at failure in pounds, $A =$ area of cross-section in square inches, l is the distance in inches from center to center of rivet holes, and r is the radius of gyration, in inches, of the cross-section of the lattice bar. The results of the tests were adjusted so that this formula applies to material having a yield point of 40 000 lb. per sq. in. These results may be considered to be applicable to "under" lattice bars. For "over" bars it seems probable that the average stress at failure would be considerably less. If $\frac{l}{r}$ is 0 in the above formula, that is, if we have a very short lattice bar, the average stress over the bar at failure would be 21 400 lb. per sq. in. If the extreme fiber stress in this short bar is 40 000 lb. per sq. in., the yield point of the material, the equivalent eccentricity of loading (e) which would produce this, may be found from the equation

$$40\,000 = 21\,000\left(1 + \frac{e \times \frac{1}{2}t}{r^2}\right),$$

where t is the thickness of the bar. The resulting e is found to be very nearly $\frac{t}{7}$. We may then regard the lattice bar to have been loaded with an initial eccentricity equivalent to $\frac{1}{7}$ the thickness of the bars.

36. *Effect of Form of Section.*—The large variation in stress over a cross-section of the column and the marked changes in stress from section to section along the column are evidently due to local crookedness, local eccentricity, lack of rigidity of lacing,

and other variations which may be independent of the general flexural curve usually assumed in deriving the usual formulas for column strength. It would seem that the form of section (including in this term the relation of the thickness of the metal to the section as a whole) has a bearing on the strength. The thinner and flimsier component angles and channels are more liable to receive kinks, bends, and distortions before and during punching and riveting in the shop and in the later transportation and erection than are the stockier sections. The value $\frac{ec}{r^2}$ of the formula given on page 54 may be expected to vary with the form of section used. Besides, some sections are better fitted to withstand lateral twisting or diagonal distortions and to preserve the integrity of the cross-section than others. The wrinkling tendency in plates and thin parts under compression, heretofore referred to, is another element affecting the strength of columns. It may be expected, then, that differences in section, in type of component parts, in method of relating and tying the parts together, and for the same type of section differences in relation of thickness of parts to extreme dimensions of sections, will have an important influence upon the compressive strength of columns. It follows, therefore, to give the best results, that the section of the column, and its web construction, should be chosen so that (1) the shop processes shall leave the component parts of the column in the best condition (giving the minimum of bending, buckling, twisting, and interior eccentricity), and (2) the section will be adapted to resist local lateral bending and twisting action. Evidently, different forms of section may be expected to give considerable difference in strength. This difference has been recognized heretofore in formulas which have been proposed and used for certain types of columns.

37. *Effect of* $\frac{l}{r}$.—A study of the tests does not show any relation between the stresses actually observed and the stresses computed by column formulas. The high stresses do not come where the curve of flexure used as the basis of formulas of the Rankine type would place them, and the position and amount of the maximum stresses are very irregular. Although there is little range in the slenderness ratio ($\frac{l}{r}$) of the columns tested, no

effect is noticeable for which the value of $\frac{l}{r}$ would seem to have much influence. This view seems to be in disagreement with theoretical considerations. The lengths for which Euler's formula may be expected to govern column strength are much greater than the length tested, and probably are higher than is generally assumed in engineering literature. Within the critical length at which Euler's formula governs, the general flexure of the column as a whole under load has less influence upon the strength of the column than is ordinarily assigned to it, and therefore the influence of $\frac{l}{r}$ is not as great as is represented in the usual column formula. Of course, the longer the column the more the amount and influence of its defects may be. The recent tests of columns at the Watertown Arsenal indicate that, within the range of lengths tested ($\frac{l}{r}$, 25 to 175), the reduction in strength at elastic limit with increased length is relatively small, perhaps not much more than may be due to increased variation from straightness and homogeneity. In this connection it should be noted that the column formulas in common use give altogether too high strengths for short columns, if the elastic limit is to govern. So far as ultimate strength is concerned, tests show the strength of short columns to be considerably above their elastic limit, but beyond a limit of, say, 35 for $\frac{l}{r}$, there is much less difference between elastic limit strength and ultimate strength.

38. *Column Formulas.*—That the column formulas in common use have limitations, has been well understood, but the effect which the conditions of the component parts of a compression member exert on the distribution of stress over the section has not been appreciated, nor has that of eccentricity of connection of latticing, and of the possible non-integrity of section. It would seem quite probable that, for columns of the same length and containing the same amount of metal, one which is of stocky form and in which the metal is distributed so as to resist local flexural and torsional action will be much stronger and more satisfactory than a column of more flimsy form, which has its metal spread in thinner sections, even though the slenderness ratio, $\frac{l}{r}$, of the for-

mer may be considerably more than that of the latter. It seems reasonable to expect that a form of section which resists lateral bending, torsional and collapsing stresses, will be much more satisfactory than a more flimsy type of column, for the lengths most common in ordinary bridge construction. If these statements are trustworthy they express an important principle. For the longer lengths, the slenderness ratio must exert a stronger influence. For the strength of the component angle, channel, or other structural shape used in a built-up compression piece, many engineers have been satisfied with the provision that the slenderness ratio of the component member shall be less for the length between the points of attachment of lacing than the slenderness ratio for the column as a whole, and have given little attention to the possible non-integrity of the section or to the probable effect of imperfections of manufacture. Fortunately, the large influence of the slenderness ratio in column formulas has given sections with which failures have not occurred. Whether a column formula should include a factor depending on the form of the section and the relative thickness of the metal, or whether the allowable stresses for any form of column should be based on experimental data for the section used, will depend on future developments.

39. *Field for Investigation.*—The tests herein recorded have shown the practicability and also the importance of making tests on the distribution of stress over built-up columns within the elastic limit, both under laboratory conditions and in field service. It is evident that much experimental information is needed on the stresses which are developed in compression members built under ordinary conditions of fabrication and erection before a satisfactory column formula may be established. Tests giving the needed information involve extreme care, and they are expensive, with regard to time and labor, whether done in the field or in the laboratory. A full study of the action of the compressive piece under loads which do not stress the material beyond the elastic limit should be included. The expenditure involved is far beyond that of tests to destruction alone. An investigation should be accompanied by a careful study and analysis of the tests and results. A program of tests need not involve a large number of test pieces; but, to be really useful for the purpose in view, the time devoted to the test and the study of each piece must be ample, and the total

cost of even a fairly comprehensive investigation will be large. It may be expected, however, that the value of the results would repay many times the cost of the work, and the expense would be justified by the added security and, perhaps, by the economy of metal which might result from the investigation.

40. *Summary.*—The main points brought out in the preceding discussion may be recapitulated as follows:

1. The practicability of making tests to determine the actual stresses which are developed under working loads and up to the elastic limit of the material in the members of a column, throughout its length and over its cross-section, has been shown. The results significantly point to the importance of making investigations of this kind. The experimental work involved is tedious and laborious, and of course, the work requires skilled and experienced experimenters. The need of such information has been recognized heretofore, but tests have not been taken up because of the supposed impracticability.

2. An important result of the tests is the evidence that considerable local flexural action exists in the channel members of the columns, such as may be produced by lack of straightness or by any method of applying the load eccentrically. This is especially true in the flimsier column.

3. The condition of flexure varies markedly throughout the length of the channel member, in some cases the maximum compression in one cross-section being at the extreme fiber on one side of the channel, and in a near-by section the other side of the channel showing the excess of stress.

4. There were also indications of sudden changes in the relative amount of stress carried by the two channels at near-by sections, indicating general flexure of the column.

5. The measurements made indicate in a number of cases stresses in the extreme fiber from 40% to 50% in excess of the average stress, and in some cases even higher.

6. The amount of eccentricity necessary to account for the increase of stress found in individual channels, based on lack of straightness and the ordinary theory of flexure, is relatively small.

7. The amount of deformation observed in lattice bars is relatively small, and its variation throughout the length of the column is quite irregular. The measurements indicate a stress in

the lattice bars which would be produced by a transverse shear equal in amount to 1% to 3% of the applied compression load, or to that produced by a concentrated transverse load at the middle of the column length equal to 2% to 6% of the compression load. The stress referred to is the average stress over the section of the lattice bar.

8. It seems futile to attempt to determine the stresses which may be expected in column lacing for central loading by analysis based on theoretical considerations or on data now available.

9. When the column was tested as a beam, the extreme fiber stress in lattice bars in compression was found to be from 1.4 to 5.5 times the average stress over the cross-section of the lattice bars, and the extreme fiber stress in lattice bars in tension was found to be 1.7 to 3.2 times the average stress.

10. Tests of individual lattice bars for load-carrying capacity under conditions which resemble those of service show that the usual form of bar is a very inefficient compression member when loaded eccentrically through a riveted connection. The ultimate strength was in no case as much as one-half of the yield point of the material.

11. The formula, $\frac{P}{A} = 21\,400 - 45\frac{l}{r}$, represents fairly well the ultimate strength of the flat lattice bars tested, based on material having a yield point of 40 000 lb. per sq. in.

12. It seems evident that the component members of a built-up column do not act together in such a way as to give entire integrity of cross-section in resisting bending.

13. The distribution of stress under working loads, and even up to incipient failure, may be different from that which exists after the column becomes crippled. This is due to the yielding of the more strained parts after the yield point is reached at any fiber, and a consequent redistribution of stress.

14. The sudden failure of a test column at a relatively low load by buckling of the lattice bars is accounted for when the amount of transverse shear developed in other test columns and the strength of lacing found in lattice-bar tests are taken into consideration.

15. No relation has been found between the stresses actually observed and the stresses computed by column formulas. The stresses do not increase toward the middle of the length of the

column, as may be expected from the Rankine form of analysis, but are quite irregular in their location and distribution.

16. Much of the excess of extreme fiber stress over average stress is evidently attributable to local crookedness of piece, eccentricity of bearing of lattice bar connection, lack of rigidity of lacing, and other irregularities that are due to the condition of the material and its fabrication, and what may be considered to be inherent variations and defects in the constructed compression piece. Within the elastic limit of the material and for the lengths most commonly used the lateral flexure of the column as a whole is very slight, and slenderness ratio can not be said to be the governing consideration. Undoubtedly, the chances for variations from the ideal column will become greater as the column length becomes greater, and these variations may have a more marked effect upon its strength.

17. It is evident that the form of section is important. Stocky and stiff component members are less liable to receive kinks, bends, and distortions during and after fabrication and will resist the effect of such imperfections with less resulting stress than will flimsy pieces. Some column sections are well calculated to resist bending, buckling, and twisting, and are so tied together as to preserve integrity of section, while others have less resistance to general distortion. Even the wrinkling action in plates and thin parts needs consideration. It seems reasonable that, for columns of the same length and containing the same amount of metal (within the ordinary dimensions), one which is of stocky form and in which the metal is distributed so as to resist local flexural and torsional action will be stronger and more satisfactory than a column of more flimsy form, which has its metal spread in thinner sections, even though the slenderness ratio, $\frac{l}{r}$, of the former may be considerably more than that of the latter. Further, a section which will come through the shop and erection processes with the least imperfections has advantages.

18. This field of investigation is a promising one, and its importance to the engineering profession warrants its being taken up in a thorough and comprehensive manner. Full information on many matters is needed before better and more nearly satisfactory column formulas may be established.

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THE STRENGTH OF OXYACETYLENE WELDS IN STEEL

BY

HERBERT L. WHITTEMORE

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ENGINEERING EXPERIMENT STATION

BULLETIN NO. 45 SEPTEMBER 1910

THE STRENGTH OF OXYACETYLENE WELDS IN STEEL

BY HERBERT L. WHITTEMORE, ASSOCIATE IN THEORETICAL AND APPLIED MECHANICS*

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*Since the manuscript for this bulletin was submitted, Mr. Whittemore has accepted appointment as Engineer of Tests of the U. S. Ordnance Department at Watertown Arsenal.

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THE STRENGTH OF OXYACETYLENE WELDS IN STEEL.

I. Introduction.

1. *Preliminary.*—Among the recent developments which give promise of wide-spread use in the field of metal working, is that of the oxyacetylene blowpipe. Due to the high temperature of the flame produced by this instrument, results are obtained which heretofore have been impossible. The most important use of the oxyacetylene flame is the welding of two pieces of metal by fusion without the necessity of adding either flux or soldering or brazing material. This process is known as autogenous welding.

This process has already become important commercially. It seems probable that when its effectiveness and availability have become known, it will be quite generally used, both by large and small metal working shops. In this connection the following facts may be noted:

(1) The combination of oxygen with acetylene produces one of the highest temperatures known,—the highest due to combustion and about equal to that obtained in the electric furnace.

(2) Methods of producing calcium carbide in the electric furnace, and methods, recently perfected, of producing oxygen by the distillation of liquid air, and by other means, have reduced the cost of these gases to the point where they are commercially available.

(3) The oxyacetylene blowpipe, formerly liable to dangerous explosions, has been perfected until entire safety is claimed.

(4) The necessary apparatus, when conditions demand extreme simplicity, consists only of a small tank of compressed oxygen and another of acetylene dissolved in acetone, both connected to the blowpipe by rubber hose. It is easily portable and can be used in almost any place or position.

(5) Skill in operating the blowpipe is readily acquired by an ordinary workman.

The general applicability of this process to welding depends upon two things: first, the strength and other physical properties of the welds; and second, the cost of the work. Of these, the first is the more important. An extensive search for data upon the matter of strength showed that very little had been published, merely a few general statements and still fewer definite ones. Most of the latter, however, appeared to be of doubtful accuracy. References to articles on this subject are given in the bibliography.

The process has been used successfully for the following work:

(1) Welding tanks and sheet metal work of all descriptions.

(2) Welding frame joints for automobiles, making a rigid structure all in one piece.

(3) Adding metal where needed, usually in small quantities; for example, eliminating defects in castings, particularly in steel castings, such as blowholes, etc., or adding metal to a piece which has been machined under size.

(4) Repairing boilers by either welding cracks, patches, etc., or adding metal where "grooving" or "pitting" has occurred.

(5) Bonding of electric traction rails by fusing the copper bond to the rails.

(6) Repairs of all kinds, made necessary by breakage. For example, a cast-iron punch press frame, broken at the throat, has been welded so that practically it is as useful as ever.

While the oxyacetylene blowpipe method of welding may be applied successfully to a very wide range of work in emergencies, such as "break-down repairs", etc., the cost of the necessary gases for welding thick pieces is so high that this method will never entirely displace coke, gas, or electric welding outfits for manufacturing conditions. Its field is especially *repair work*, *field work*, and manufacturing operations on *pieces of small cross-sectional area*, say, plates not exceeding $\frac{1}{4}$ in. in thickness.

2. *Scope of Tests.*—The experiments recorded in this bulletin were undertaken with the aim of adding to the information regarding the strength and other physical properties of oxyacetylene welds in steel, inasmuch as steel is the most important metal used in commercial construction. The number of tests was made large enough, it is hoped, to make the results representative of the results which may be obtained under favorable commercial conditions. Although circumstances limited the work to a small range in the thickness of the steel plates, an attempt was made to determine the effect of other variables, such as thoroughness of fusion, forging and heat treatment, and flame regulation, which might have an effect on the welds.

Little attention was paid to the matter of cost of welding the test pieces, as data of cost are of doubtful value unless obtained under commercial conditions. Several of the references listed under VI. Bibliography discuss this matter quite fully, and the firms supplying oxyacetylene welding apparatus are willing to undertake work for prospective customers and thus determine experimentally the time and materials required. In any case, there should be no excuse for operating a blowpipe for any length of time under commercial conditions without estimating the cost, but to obtain data on the strength of the welds requires apparatus and time not usually available, so that there is likely to be much doubt on the latter subject even where the process has been in use for long periods of time.

Incidentally, an investigation was made of the effect of flame regulation upon the strength of the weld and upon the proportions of oxygen and acetylene in the blowpipe flame. The record of experience in blowpipe manipulation and skill in welding as the work progressed, together with other information obtained, will, it is thought, be of service to users of the oxyacetylene blowpipe.

3. *Acknowledgment.*—The apparatus used was a part of the equipment of the Laboratory of Applied Mechanics of the University of Illinois, and the work was carried on in the Laboratory as an investigation for the Engineering Experiment Station. All the work of welding and testing was done by the writer.

In making the chemical analyses of the gas samples, valuable assistance was rendered by R. H. Jesse, Jr., Ph. D., of the Chemistry Department, University of Illinois, to whom much of the credit for this part of the work is due.

4. *Historical.*—The oxyacetylene blowpipe is an outgrowth of the blowpipes in common use which are supplied with coal gas and air. Attempts to increase the temperature of the flame led to the use of combustible gases having higher thermal values per unit of volume, and to the use of pure oxygen. In this way, a given number of heat units, produced by the combustion, were confined to the smallest possible volume of gas. The use of pure oxygen eliminated the nitrogen present in the air which served only to dilute the gases and to lower their temperature in a corresponding degree. The result of these changes was to bring

into use the oxyhydric blowpipe, which is extensively used in Germany for the autogenous welding of steel and for other work.

Acetylene, as a substitute for hydrogen, offered theoretic advantages, as its thermal value is 1846 British thermal units per cubic foot. This amount is over six times the thermal value of hydrogen, which is 293.5 British thermal units. Attempts to use acetylene, however, resulted in serious explosions. The first successful oxyacetylene blowpipe was devised by E. Fouché, a French investigator, who experimentally determined the rate of propagation of an explosion in tubes of varying cross-section, when they were filled with an explosive mixture containing acetylene. He then perfected a blowpipe in which the acetylene is supplied through small tubes at a rate greater than that of the propagation of the explosion back toward the acetylene reservoir. While this precaution would, apparently, be unnecessary if the tubes contained only pure acetylene, there is always some danger that, on account of imperfect operation, the oxygen which is under higher pressure than the acetylene will be forced into the acetylene passages or even into the reservoir itself.

In order that use may be made of the acetylene gas under the pressure at which it is usually generated (about 20 in. of water or less) the Fouché blowpipe uses the oxygen under pressure to draw the acetylene into the blowpipe on the injector principle. This avoids the necessity for an expensive compressor for the latter gas.

Fouché invented his blowpipe probably about 1902 or 1903, but the process was not introduced into this country until 1904, when the Fore River Shipbuilding Co., of Quincy, Mass., installed oxyacetylene blowpipes for welding light sheets of metal which had formerly been riveted.

Several blowpipes have since been designed to use both gases under pressure, and they are said to have the following advantage over the Fouché blowpipe. Both gases, being under pressure, maintain quite accurately their relative proportions when once properly adjusted. In the injector blowpipes, on the contrary, changes in temperature of the blowpipe and the copper tip forming the outlet cause some variation in the size of this opening and consequently variations in the relative proportions of the gases.

II. Welding Apparatus and Methods.

5. *Apparatus.*—The Fouché blowpipe was selected for these experiments because it is probably the best known and most widely used. While there may be differences among various oxyacetylene blowpipes in regard to convenience of operation, there can be very little difference in the efficiency of joints welded by these various blowpipes.

A welding equipment was secured from the American firm controlling the Fouché patents. It consisted of a Fouché blowpipe, a hydraulic back-pressure valve, a tank of compressed oxygen, an oxygen pressure regulator, a pair of blue glasses and a rubber hose.

In order to avoid the trouble and expense of an acetylene generator for this work, tanked acetylene was secured from The Commercial Acetylene Company, 80 Broadway, New York, from their plant at Joliet, Illinois. For commercial work of any magnitude, acetylene would usually be generated, as the cost would then be about one-third that of tanked gas. Tanked acetylene offered advantages for experimental work, among which were the probability of a more uniform quality of gas than would have been obtained from a generator, and also the possibility that the gas was more nearly pure. This company furnished a tank of acetylene, a high pressure gauge, and an acetylene pressure regulator.

6. *The General Arrangement of Apparatus as Used.*—The apparatus was arranged as shown in Fig. 1, the parts being as follows: A, work bench, covered with fire brick; B, blowpipe; C, oxygen pressure regulator; D, oxygen tank; E, hydraulic back pressure valve; F, acetylene pressure regulator; G, water U–tube for pressure of acetylene as supplied to blowpipe; H, gauge for acetylene tank pressure; I, acetylene tank.

The arrangement of the oxygen connections and of the acetylene connections is shown in Fig. 1. The acetylene supply is connected to the back pressure valve E. The hose J–K conveys the gas from the back pressure valve to the blowpipe. The oxygen tank is shown with its pressure regulator, C, the gas passing to the blowpipe through the hose L–M.

7. *Oxygen Supply.*—The oxygen tank had a capacity of 100 cu. ft., when charged to 120 lb. per sq. in., and weighed, empty,

132 lb. The oxygen was about 95% pure, nitrogen being the principal impurity.

In order to maintain a constant pressure suitable for use in the blowpipe, a regulator was attached to the oxygen tank. This is shown in Fig. 1. The pressure gauge, N, measures the tank pressure and allows computations to be made, at any time, of the amount of oxygen remaining in the cylinder. The thumb screw P adjusts the pressure of the gas as delivered to the blowpipe, which is measured by the pressure gauge O.

8. *Acetylene Supply.*—The acetylene tank had a capacity of 225 cu. ft., when charged to 150 lb. per sq. in. pressure. The tank was 12 in. in diameter by 36 in. long and weighed 120 lb. These tanks are packed with asbestos disks before the ends are closed. The asbestos is then saturated with acetone (a species of wood alcohol,) which at 10 atmospheres, or 150 lb. per sq. in. pressure, absorbs ten times its own volume of the gas at a normal temperature, thus increasing the storage capacity of the tank tenfold. Absolute safety for this method of storage is claimed by the manufacturers from whose catalog the above information regarding the tank was obtained. Analyses made by the firm supplying the acetylene indicate that the gas used was about 99.6% pure.

The acetylene tank I with its valve Q is connected by a pipe to the constant pressure regulator F. The pressure gauge H measures the pressure in the acetylene tank; with the pressure known, the amount of gas contained at any time may be computed.

This regulator was not provided with means for adjustment, but a pressure in the outlet pipe of about 12 in. of water was maintained. A U-tube filled with water and connected into this outlet pipe, (G, Fig. 1), allowed this pressure to be measured. It varied somewhat, depending partly upon the amount of water in the back pressure valve.

9. *Hydraulic Back Pressure Valve.*—A section through this valve is shown in Fig. 2. Water is supplied through D and G, and brought to the proper level, E, by opening the cock F, and draining any excess, after which F is closed. The acetylene enters through the cock B and bubbles up through the water, then passes to the blowpipe through cock C. If, for any reason whatever, the direction of flow is reversed, the water level at E

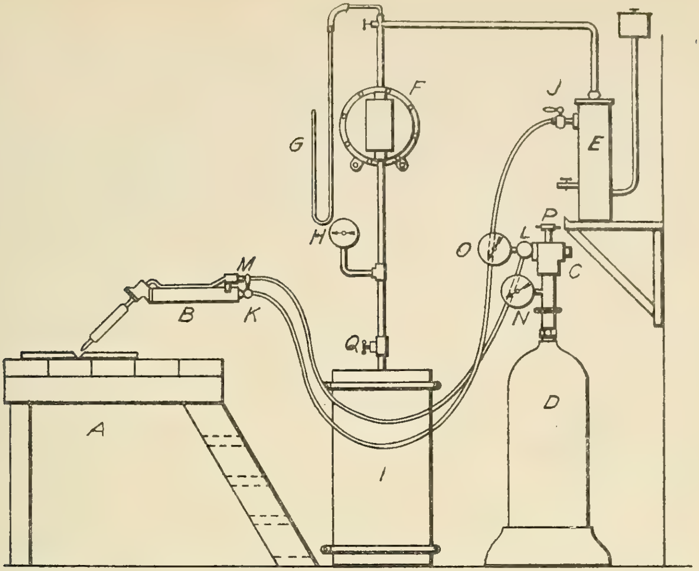


FIG. 1. GENERAL ARRANGEMENT OF OXYACETYLENE WELDING APPARATUS.

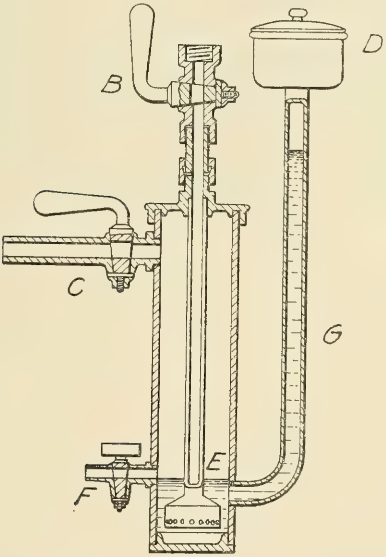


FIG. 2. BACK PRESSURE VALVE FOR ACETYLENE.

falls, the water in G rising until a free passage is provided through G and D to the outer air. This makes it impossible for oxygen to pass into the acetylene passages further than the back pressure valve.

10. *Blowpipe.*—The Fouché blowpipe is shown in Fig. 3. The oxygen enters at A and the acetylene at B. The amount of acetylene is regulated by cock C, which, therefore, controls the relative proportions of the two gases. The sizes, with their capacities and gas consumption, are given in Table 1.

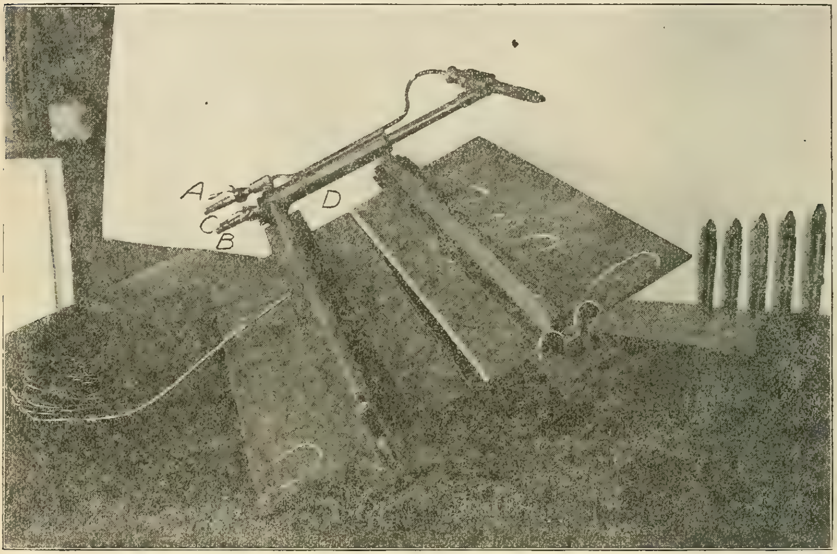
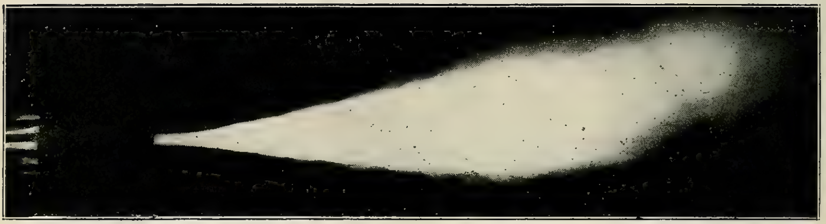


Fig. 3. Fouche Blowpipe with Removable Tips and Test Strip Ready for Welding—Second Method.

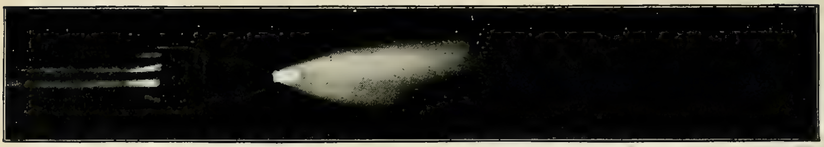
Each of the above sizes is intended for use only on plates of the thickness stated. The use of an unsuitable size of blowpipe will result in loss in economy.

11. *General Methods of Welding.*—There are two methods of making autogenous welds. The first, suitable for thin plates, requires that the edges be brought into perfect contact. They are then fused together without the addition of any material. The second, used for thick plates, consists in fusing into a groove formed by the beveled plate edges, material similar to that in the plate. The thickness generally given as the dividing line between

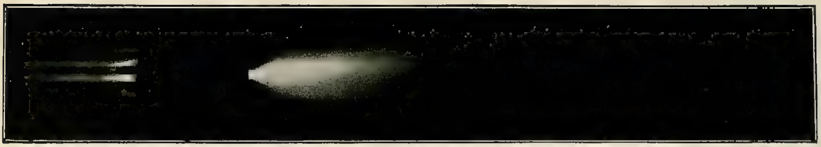


(a) Acetylene Flame in Air.

(b) Excess-acetylene Flame (Double Cone).



(c) Normal or Correct Oxyacetylene Flame.



(d) Excess-oxygen Flame (Short Cone).

Fig. 4. Variations in the Flame of the Blowpipe.

the two methods is $\frac{1}{4}$ in. The No. 7 blowpipe was selected on this account, as with it both methods of welding could be investigated. This size also allowed the use of specimens having fairly large cross-sectional areas without the unduly great cost of operation of the larger sizes.

TABLE 1.

SIZES AND CAPACITIES OF FOUCHE BLOWPIPE.

Blowpipe No.	Approximate Thickness of Sheet or Plate, inches	Approximate Consumption, cu. ft. per hour	
		Oxygen	Acetylene
2	$\frac{1}{32}$	2	1½
3	$\frac{3}{64}$	4	2½
4	$\frac{3}{32}$	6	3¾
5	⅛	10	6
6	$\frac{3}{16}$	16	10
7	¼	25	15
8	⅜	36	22
10	½	45	28
12	⅝	65	40
15	¾	100	60

NOTE: For copper plates, larger blowpipes are required than for steel plates of corresponding gauge.

12. *Regulation of the Blowpipe.*—Given the gases supplied under constant pressure, the proper proportioning of the two is obtained by adjustment of the cock C, Fig. 3.

The operator is governed in the regulation solely by the appearance of the blowpipe flame. Slight variations in the proportions caused relatively large variations in the appearance of the flame. This is well shown in Fig. 4, reproduced from photographs of the flame itself. The combustion of acetylene alone (see (a)) gives an intensely white flame of large volume with a heavy formation of soot at its outer end. When oxygen is added, the flame shortens (see (b)) and the combustion is more nearly complete, as is indicated by the nonformation of soot. There is then one small cone close to the tip of the blowpipe which is intensely white. This is surrounded by another white cone which in the cut partially masks the inner cone. Both are perfectly visible to the eye, particularly when observed through blue glasses. Beyond these two white cones is a nearly colorless flame of large volume.

Proper regulation is obtained by reducing the amount of acetylene until only one white cone is visible, as shown at (c), with a colorless flame as before. This single white cone is with the No. 7 blowpipe about $\frac{1}{8}$ in. in diameter and $\frac{5}{16}$ in. long, and has a rounded end. If the acetylene is reduced still further, the cone shortens as shown at (d). Proper regulation is effected when the flame is seen as a single cone of dimensions as large as possible. This is the operator's chief guide. As it is difficult to determine by inspection when this cone has shortened, especially after work has been in progress several minutes, it is convenient to increase the supply of acetylene until two cones appear, then decrease it until the second cone disappears.

References No. 1 and 2 under VI. Bibliography give descriptions of the various flame characteristics and a discussion of the chemistry of the combustion.

III. Test of Welds.

13. *General Plan of Tests.*—As these experiments were undertaken to ascertain the strength of welds as made by a workman of moderate experience, a large number of specimens were prepared for tensile tests. While the statement is often made that the strength of the weld is affected by conditions which are practically beyond commercial control, such as the purity of the gases and the material to be welded, and also, possibly, the construction of the blowpipe, these factors were all disregarded, as they were probably constant in this work and more especially as they duplicated accurately the conditions which exist in commercial work. The skill and care of the operator, without a doubt, are chief factors in controlling the quality of the welds. The effect is especially noticeable when the operator is utterly without experience, as was the case when this work was started. Attention was therefore concentrated on the proper blowpipe manipulation, and the number of test pieces was made great enough to provide considerable practice, which, it was hoped, would show an increase in the strength of the welds as skill was acquired.

The general plan of preparing and testing specimens for tests of strength of welded joint may be seen from Fig. 5. A plate of steel was cut into strips A, B, C, etc., and from the ends of each strip test pieces were cut which were tested in tension to give the strength of the plate material. The remainder of the strip was then cut in two lengthwise. These cuts are shown in Fig. 5 (a), by broken lines lengthwise of the strip. The two parts were then welded together and the welded strip cut across the weld into specimens as shown by the cross-wise lines in Fig. 5. Each strip was about 2 ft. long by 1 ft. wide. In the first series of tests the strips were so arranged that some specimens were cut in the direction of rolling and others perpendicular to the direction of rolling. The specimens were then tested in tension.

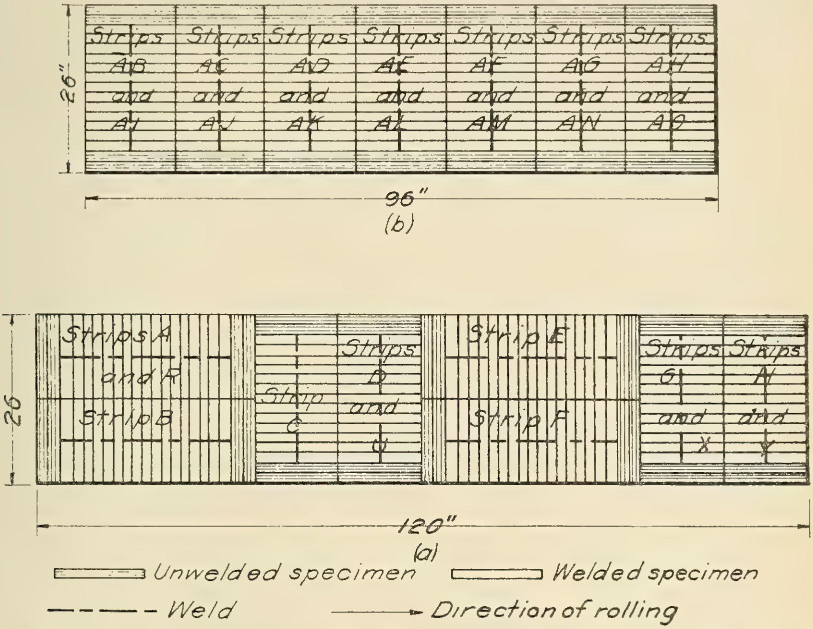


Fig. 5. Location of Strips and Test Specimens in Steel Plates.

14. *Preliminary Tests.*—Some welding practice was obtained by welding pieces of band iron 0.135 x 1.344 in.; about 50 such welds were made and tested. The actual blowpipe time required, as computed from the amount of oxygen used, was 2.16 hours.

This band iron, unwelded, had an average ultimate strength of 62 300 lb. per sq. in. and a yield point of 46 400 lb. per sq. in. with an elongation in 4 in. of about 20%. When welded the values for all these properties were lower than in the unwelded material. The loss was about 5.7% in the yield point, 30% in the ultimate strength, and 88% in the elongation. The results of these preliminary tests are not considered of sufficient importance to be recorded here.

This work was excellent considering that the operator had no previous experience and no instruction except that contained in the printed directions accompanying the apparatus. It should also be remembered that the blowpipe was much too large for this thickness of metal so that the material was undoubtedly over-heated.

A. FIRST SERIES OF TESTS.

15. *Specimens.*— The main object in this series of tests was to provide practice in the use of the blowpipe, and to bring out, if possible, the variables affecting the strength of the welds. In general, the efficiency of the welds was found to be low, and a constant effort was made to find the cause of the low strength and its relation to the appearance of black or dark blue spots in the fracture.

Four flange steel plates were secured from Joseph T. Ryerson and Son, Chicago. The plates were 26 × 120 in. and $\frac{1}{4}$ in. thick. The method of preparing specimens was that described under 13. General Plan of Tests. A whole strip was cut into 16 specimens about $1\frac{1}{2}$ in. wide and 13 in. long, and these were tested in tension to failure. In this way the properties of the weld at every portion of its length were determined. The material would have been injured had the metal been sheared, so the cuts were made on the planer or shaper with a cut-off or parting tool. As this proved to be a tedious job, after the first few strips a power hacksaw was used and proved satisfactory.

For filling, very soft open hearth steel wire No. 14 (0.079 in. in diameter, actual measurement) was used. This was also purchased from Joseph T. Ryerson and Son. The physical properties of this wire, as determined by tension tests, were as follows:

Ultimate strength, lb. per sq. in.,	64 400
Yield point, (about) lb. per sq. in.,	37 500
Elongation in 10 in., per cent,	15
Reduction of area, per cent,	74

No analyses of gas or material were made for this series of tests.

16. *Method of Testing.*—The testing was done in a 100 000-lb. Riehle testing machine having an autographic attachment. The dimensions of the specimens were first carefully taken. A thread micrometer with contact surfaces about $\frac{1}{32}$ in. in diameter was used for obtaining the thickness. Great care was necessary in this measurement, because of the roughness of the surface of the weld when it remained as it came from the blowpipe. The surface of the specimen was divided in such cases into strips $\frac{1}{4}$ in. wide, and the micrometer readings for thickness were taken at the center of each strip and averaged for the thickness of the specimen.

A 6-in. gauge length was laid off each specimen and marked with a center punch. The shortness of the specimens made an 8-in. gauge length impracticable. When placed in the machine, the clamps for the autographic apparatus were secured to the specimen at the punch marks and a record made as the test progressed. From this the yield point and ultimate strength of the specimen were determined with sufficient accuracy for this work. A copy of a number of such records is shown in Fig. 6. The elongations were measured with a steel scale from the specimen after rupture, not from the graphical record.

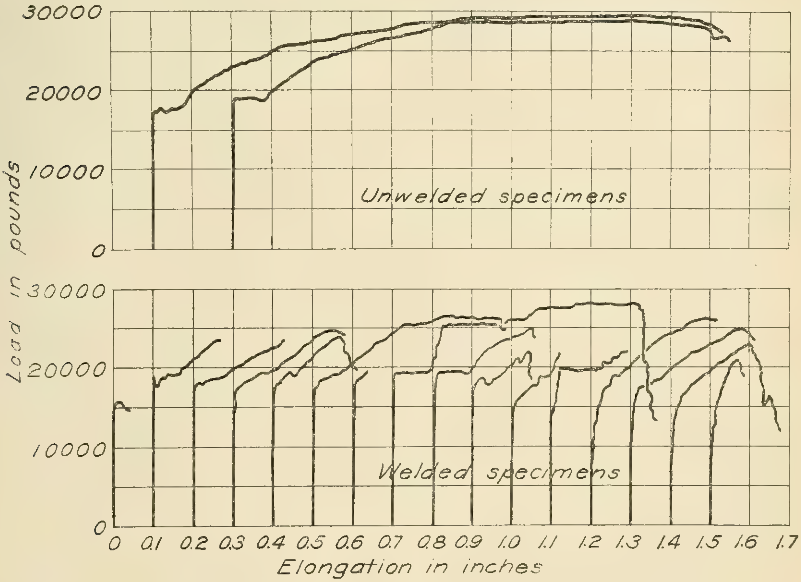


FIG. 6. AUTOGRAPHIC TENSION-TEST DIAGRAMS OF WELDED AND UNWELDED SPECIMENS.

The stresses at yield point and ultimate strength were computed by dividing the load from the graphical record by the actual original area at the place where the rupture occurred, usually at the weld.

The efficiency of the weld was determined by dividing the ultimate unit-stress (when rupture occurred at the weld) by the average ultimate unit-stress of the unwelded specimens, for the same section of the plate. Thus:

$$\frac{\text{Ultimate stress in weld}}{\text{Ultimate stress of unwelded material}} = \text{Efficiency of weld.}$$

This efficiency is then the ratio of the strength of the weld to the strength of the material, and measures, in some degree, the value of the welding process.

17. *Manipulation and Preparation.*—In this, as in the preliminary work, an attempt was made to follow all instructions given in the manufacturer's circular as closely as possible.

These may be summarized as follows:

Commence welding at nearest point and work away from the operator. (See 26. Improvements in Methods of Welding.)

Attend carefully to the regulation of the flame.

The apex of the small flame cone should be in contact with the metal to be welded. (See 26.)

The blowpipe should be held at a constant distance from the work and advanced slowly and regularly with a slight oscillating or circular motion,

When adding metal to the weld, care must be taken not to let the full force of the flame play on the rod or wire unless it is in contact with the pieces being welded which will prevent its being overheated.

Material being added must come in contact only with metal which is fused, otherwise welding does not occur.

The blowpipe was directed against the sides of the joints until the fusion occurred, and the slight circular motion of the flame caused the molten metal to flow together at the bottom. The blowpipe was advanced, still describing small circles, as fast as this weld was formed for an inch or two, then a return was made to the starting place and the metal again brought to a state of fusion. The wire was then fed into the small pool of liquid steel until the blast from the flame threatened to blow it over against comparatively cool steel. The blowpipe was then swung in larger circles which extended the area under fusion somewhat, while allowing the center of the pool to harden. These pools of molten steel were from $\frac{1}{2}$ to 1 in. in diameter. Another pool was then formed just beyond the first so that their edges overlapped. (This method was changed later. See 26. Improvements in Methods of Welding.)

The plates for this series were clamped as shown in Fig. 7, to hold them in their proper relative positions and with their surfaces in the same planes. The thumb-nuts were not tightened sufficiently to prevent the plates from drawing together as the welding proceeded. Unless otherwise stated, the plates were beveled as shown in Fig. 8 (a), and clamped with the edges at one end of the joint in contact, and at the other end $\frac{1}{2}$ in. apart to allow for "creeping". Welding was started at the closed end of the joint. The single strands of soft steel wire, No. 14, were used for filling.

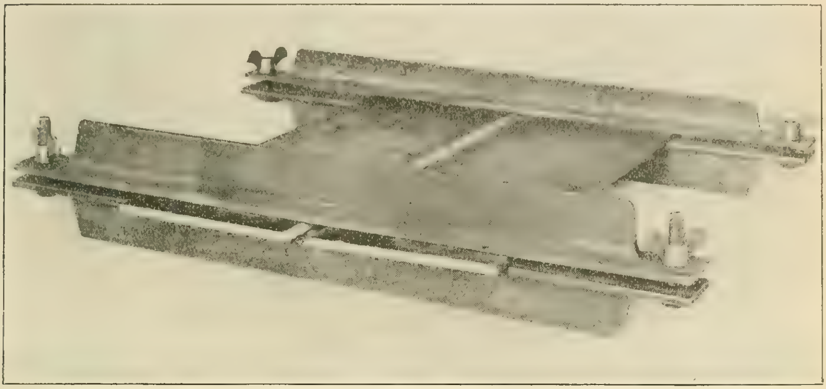


Fig. 7. Strip Clamped Ready for Welding.

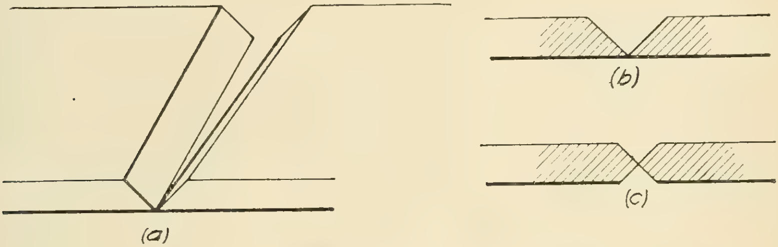


Fig. 8. Plates Beveled for Welding.

In adding the wire, difficulty was found in preventing the playing of the full flame on the wire when the blowpipe was given a circular motion; so at times, it was held nearly stationary and the steel wire pushed, as rapidly as it melted, into the pool just beside the flame. Working in this way, it took some time to build up the required thickness of metal at the weld. If depressions appeared after cooling occurred, the surface was again fused and more wire added until, as far as could be determined by inspection, no portion of the welded surface was below the adjacent surfaces of the plates. This series of operations was repeated until the weld was completed.

At times, in welding together the bottom of the groove before adding wire, the metal became too hot and dropped away, leaving an opening which the strong blast of the flame quickly enlarged. In such cases it became necessary to fuse the edges by passing the flame over the opening rapidly, while adding wire as rapidly as it fused, leaving a short length in the opening. When enough metal had been added to prevent the flame from passing through the opening, the whole mass was thoroughly fused together, forming a weld across the bottom of the groove. Wire was then added, as before, to build up the thin place, care being taken not to direct the flame against it too continuously.

The general appearance of such a joint is well shown in Fig. 9 and 10, taken from strip E after welding. Fig. 9 shows the upper side from which the work was done, and Fig. 10 the bottom where the edges were practically in contact before welding commenced. In Fig. 9 the pools forming the weld are shown. They are covered with black oxide formed by the oxygen of the air on the white hot metal left by the advancing blowpipe. The concave centers appear somewhat spongy on the surface but a file shows the bright, clean metal just below. The lighter portions of the plate show the metal which has been heated to redness but not to fusion on each side of the weld. The work proceeded from left to right in this case. In Fig. 10 is again shown the metal which has been heated to redness and also the excrescences of wire and molten metal which passed through gaps in the thin edges. This occurred at about three places in this weld. While not apparent in the photograph, this bottom sagged of its own weight while hot, aided, of course, by the blast from the blowpipe, so that the line of the weld was raised somewhat above the adjacent surfaces thus tending to thicken the metal at the weld. Probably this never exceeded $\frac{1}{16}$ in.

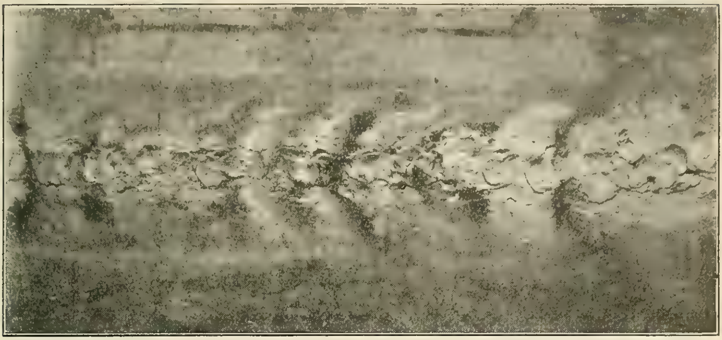


Fig. 9. Upper Side of Weld Made by "Pool" Welding.

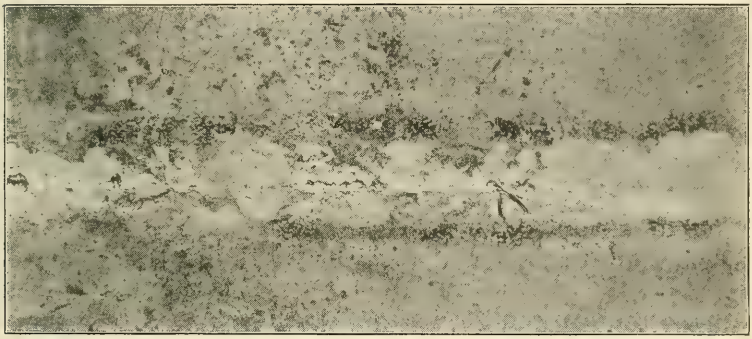


Fig. 10. Under Side of Weld Made by "Pool" Welding.

18. *Strip A.*—In the first strip tested, the general methods of welding, cutting, and testing specimens described in the preceding paragraphs were followed. One of the clamps was removed after the welding had progressed about half the length of the joint. After cooling it was found that the plates had been drawn up at their outer edges on account of the cooling of the comparatively large body of molten metal near the upper surface, so that they formed a shallow trough or V. While the section was almost flat where the welding started, on account of its having cooled while held by the clamp, at the other end of the weld where the clamp had been removed, the sides were fully an inch above the joint.

While the welding had been in progress, the edges had been drawn together just ahead of the blowpipe by the cooling of the joint just back of it. The amount allowed for this "creep" ($\frac{1}{2}$ in.) was hardly sufficient, as the thin edges appeared to crowd, thus tending to overlap. The strip was cut into specimens and these were tested without being straightened, although severe bending stresses were undoubtedly imposed on the material on the concave side of the specimen, thus tending to lower the strength of the weld. The data for these specimens are given in Table 2. The appearance of the metal in the welds after rupture is shown in Fig. 11. In most cases the silky fracture of the unwelded specimens is altered to crystalline in the welds, probably on account of the rapid cooling from a liquid state without rolling or other working of the metal. At intervals dark spongy spots, black or blue in color, occur in the weld. When questioned regarding them, the blowpipe manufacturer claimed that any discoloration must be due to burnt metal caused by an excess of oxygen in the welding flame.

The average efficiency of these specimens was 69.3%, the highest, 90.7% and the lowest 47.7%. A gradual decrease was noted as the welding of the strip progressed, due, very probably, to the fact that specimens were not straight when tested, although the data are insufficient to verify this.

For specimens having an ultimate strength below that of the yield point of the material, the weld fails before the material in the remainder of the specimen is stressed to the yield point. Although the material in the weld is probably somewhat brittle, it is so small in amount that little or no elongation would be observed on a 6-in. gauge length even if it were as ductile as the remainder of the specimen.

When the strength of the weld is above the yield point of the material, then the material throughout the length of the specimen elongates until the rupture occurs. This rise in the elongation was very noticeable for specimens 6 to 9, inclusive, for strip A.

The length of the welded portion is so small in comparison with the length of the specimen that the yield point at the weld could not be determined with accuracy, and hence the yield point of the welded specimen is not considered especially significant.

19. *Strip B.*—The preparation and manipulation used for strip A were followed as closely as possible for strip B, except that the allowance for "creep" was $\frac{5}{8}$ in. instead of $\frac{1}{2}$ in. This was found to be too much, as the plates did not draw together sufficiently to close the bottom of the groove, and consequently the flame melted through at frequent intervals.

When the weld was about half completed, work was stopped to lengthen the thread on one of the thumb bolts. This allowed the plates to cool and they warped and twisted badly. The unwelded edges of the groove overlapped about $\frac{1}{2}$ in. at the further end of the section so that satisfactory completion of the weld was impossible. The specimens were cut from the good weld and tested as before. The data are given in Table 2.

The average efficiency was 68%, the highest 79% and the lowest 56.3%.

20. *Strip C.*—This strip was welded in the same way as the two previous strips. The allowance for "creep" was $\frac{1}{2}$ in. and the section was practically flat when cold. The rough surfaces of the welds were ground practically smooth on an emery wheel before measuring the thickness. The width was divided into three strips, each about $\frac{1}{2}$ in. wide, and the thickness was measured at the middle of each as before. All welds in this strip and in all strips later tested, unless otherwise stated, were ground smooth, as by so doing the area of the weld could be more accurately determined. The emery wheel was of a medium coarse grade and used dry but the specimens were cooled frequently in water and some care was taken not to heat them enough to cause much "bluing" of the steel surface, as an annealing effect upon welds might result. See Table 2 for data.

The average efficiency was 74.3%, the highest 90.5% and the lowest 52.7%.

21. *Strip D.*—This strip was welded as usual except that an attempt was made to determine the effect of variations in the flame regulation, which were intentionally made excessive. The allowance for "creep" was $\frac{9}{16}$ in.

Specimens No. 5 to 8, inclusive, were welded with the regulation as perfect as possible, while for 9 to 12, inclusive, there was a decided excess of acetylene, and for 13 to 15, inclusive, a decided excess of oxygen. In the second lot, the second cone of the flame, Fig. 4b, was, as nearly as could be judged by the eye, 150% of the length of the first cone, both being measured from the blowpipe tip. In the third lot, the first cone, Fig. 4 (d) was shortened to little more than 50% of its length when properly regulated. Fig. 4 (c) shows the flame properly regulated. See Table 2 for data.

The average efficiency was 64.5%, the highest 79% and the lowest 52.7%.

22. *Strip E.*—As the effect of varying the regulation of the blowpipe with the previous section did not appear to have a marked influence upon the strength of the weld, it was decided after some consideration that possibly the single strands of No. 14 wire which had been used for filling up to this time, might become overheated in the blowpipe flame and thus be the cause of the burnt spots and the low strength. In order to try a larger cross-section of filler rod, four strands of wire were twisted tightly together for this section. This gave a large surface exposed to the action of the flame so that melting occurred rapidly, but at the same time gave a larger body of metal to absorb the heat and fill the groove rapidly. See Table 2 for data. Specimen No. 12 broke 2 in. from the weld.

The average efficiency was 69.2%, the highest 80.5% and the lowest 54.6%.

23. *Strip F.*—The allowance for "creep" was ½ in. Four-strand filling was again used. As in previous work, the blowpipe tip became heated from the weld, as the tip of the flame was kept approximately in contact with the surface of the metal. A gradual increase in the amount of acetylene for proper regulation was found necessary, due to this increase in temperature. Several times the acetylene cock was open wide so that further regulation was impossible. When this occurred, the blowpipe was cooled in water which restored the original conditions as regards regulation. Upon the whole, the flame regulation for this section was quite poor.

The surface of the welds was purposely not ground, in order to avoid any annealing effect due to the heating caused by the dry emery wheel. See Table 2 for data. The low percentage of elongation for the unwelded specimens is due to the fact that they all broke outside the gauge length.

The average efficiency was 66.8%, the highest 74.9% and the lowest 55%.

24. *Strip U.*—As the welds with beveled edges did not increase noticeably in efficiency, a butt weld was tried. This strip had square edges which were practically in contact along the seam before welding. This may be expressed by saying that the edges of the plates were beveled at 90° instead of 45°, as in previous strips. No filling material or wire was added..

The plates were clamped as usual with no allowance for "creep," as it was supposed that the square edges would prevent any tendency to overlap due to the contraction of the metal in the weld. This, however, proved to be an error. After the weld was finished and the plates cooled, they were found to be badly warped. When three corners were on a plane surface, the fourth was about one inch above it. They had also crowded together so that while the weld started with the surfaces of the plates flush, after about two-thirds of the weld had been completed they were offset $\frac{1}{8}$ in. and at the end offset $\frac{1}{16}$ in. The end was, of course confined closely by the clamp there. Evidently allowance should have been made for creep.

The welding was performed by causing fusion of the metal on one side only of the seam and causing the metal to flow together by the blast of the flame as it was swung back and forth. The metal was melted as deep as seemed possible and left rough with no attempt to add metal or grind the weld.

The flame was well regulated throughout, as it was frequently adjusted and never became hot enough to require cooling. After the weld was about half complete, the regulation remained practically constant until the work was finished. With the beveled seam the blowpipe tip becomes highly heated, due to the reflection from both sides of the groove. With the butt weld the blowpipe was further from the metal, generally, and maintained its regulation after reaching an approximately constant temperature. See Table 2 for data and Fig. 11 for appearance of fracture. Fig. 11 shows very clearly that the welds extended only a little way below the surface of the plates. The metal which has been melted shows a coarse crystalline fracture. Below that is a band of white metal which probably became pasty in welding but did not fuse thoroughly. This metal appears to unite to a slight extent but the weld there is weaker than through the molten metal. Below this, again, is a band of dark metal which was unaffected by the flame but was heated enough to oxidize on the surface wherever exposed to the air. The ragged appearance of this band, as in specimen 6, was due to a slight tearing of the metal surface by the dull cutting-off tool. Whereever this dark band appears on only one of the two pieces for each specimen, as in 13 and 14, it shows the amount of-offset as explained above.

The average efficiency was 54%, the highest 74% and the lowest 35.1%. Considering the small areas actually fused and welded, this seemed quite remarkable.

25. *Strip Y.*—The allowance for creep was $_{16}$ in. The plates were squared and the other conditions were the same as in strip U. They were welded from both sides without the addition of filling material.

The blowpipe was well regulated, particularly as the acetylene was readjusted to make sure of proper regulation after completing about 2 in. of weld. See Table 2 for data and Fig. 11 for appearance of fracture. As in the previous strip the band of white, noncrystalline metal through the middle of the fractures probably shows metal which was not melted.

A great increase is shown in the strength of the welds as work proceeded, but this may partly be accounted for by possible errors in measuring the thickness of the weld. The rough surfaces of the weld made accurate readings of the thickness impossible. As there was a tendency to measure the least thickness near the desired point, the average thickness and consequently the area are probably too low, thus causing the calculated stresses to be high proportionally.

The average efficiency was 82.4%, the highest 118% and the lowest 43.5%.

26. *Improvements in Methods of Welding.*—An engineer for the blowpipe manufacturers, Fred W. Wolf, Jr., was present when some of the specimens from the last three strips were tested. He discussed methods of welding and demonstrated the use of the blowpipe. Some days later, further instruction was obtained from an experienced welder employed by the same company.

While the manipulation used in making the welds up to this time was satisfactory, there were some ways in which the work could be more easily performed. It appeared likely that the adoption of such changes would also result in increased efficiency of the welds. These points may be briefly summarized as follows: Some workmen have found it preferable to work toward the operator rather than away from him, as was done in these welds. In working away from the operator, almost necessarily the blowpipe flame is directed toward the unwelded portion of the plates, making, perhaps, an angle of 60° with the completed weld. The blast from the flame tends to force melted metal from the end of the weld over upon colder metal with which it does not unite and to make it difficult to build up the filling material to the required thickness.

If, instead, the work progresses toward the operator, the blowpipe being held as described above, except that the blowpipe head makes an angle of about 120° with the finished portion of the weld, the flame strikes the sloping surface of the molten metal at the end of the weld more nearly perpendicularly and has less tendency to displace this metal.

Instead of welding in the bottom of the groove for a short distance, then forming a pool of molten metal of the required depth above it, it seems preferable to add constantly very small portions of the filling wire to the advancing surface of melted metal in the groove. If the work is done toward the operator, this procedure is comparatively easy. The sides and bottom of the groove become melted by the time the weld reaches them and the filling wire can be added uniformly to the comparatively small area of molten metal forming the end of the weld. This area advances, gradually, parallel to itself at all times, which was not the case when pools were formed.

To assist in keeping the molten metal in place, the plates may be inclined upward in the direction in which the weld is advancing. A rise of about an inch to the foot is sufficient.

Instead of keeping the tip of the flame constantly in contact with the molten metal it is advisable to increase the distance. If removed too far, the metal will not melt rapidly, and satisfactory work is impossible, so that experience shows that it is desirable to bring the flame in contact with the metal when working on cool metal, then gradually to withdraw the flame as long as satisfactory progress is being made.

Trial showed that the modified methods of carrying on the work aided considerably in *making* the welds, at least, and they were used in subsequent work. Often, after welding had started, and the metal became well heated, the flame could be removed from the work so that the distance from the tip of the flame to the metal was about equal to the length of the first cone. This apparently had no effect upon the progress of the work from the standpoint of rapidity of fusion, and did have two advantages. On account of the increased distance from the hot metal, the blowpipe did not become so highly heated, and after a short time maintained such a temperature by radiation, etc., that practically constant flame regulation was preserved. Frequent cooling of the blowpipe in water was therefore unnecessary; consequently, there were fewer interruptions to the work.

The greater distance from the metal also decreased considerably the number of "back fires", or small harmless explosions within the blowpipe. This will be evident when it is explained that the acetylene and oxygen unite to form an explosive mixture within the head of the blowpipe, but, as a rule, burn only upon issuing from the tip of the blowpipe. If the gases within the mixing chamber were stationary, the flame would be transmitted backward at a definite rate through the tip of the blowpipe and would cause an explosion or "back fire" in the mixing chamber of the blowpipe. The gases then continue to burn within the mixing chamber if oxygen and acetylene are supplied. Usually, however, the velocity of the gases out through the blowpipe tip is greater than that of the propagation of the explosion back into the mixing chamber, so that the gases burn quietly outside the tip. A "back fire" is caused by reducing the velocity of discharge through the tip, usually by obstructing the opening, as when the blowpipe is passed too close to the weld or other object. Increasing the distance of the blowpipe from the weld makes it much easier to avoid "back fires" from this cause.

Previously, when a "back fire" occurred, the acetylene was shut off, a procedure which in a few seconds extinguished the flame within the mixing chamber and allowed the blowpipe to be relighted. By observing an experienced operator, it was found that all that was necessary to extinguish a "back fire" was to close the tip completely for an instant, by brushing the tip across the clothing, then to relight the blowpipe by directing it upon the hot metal in the weld. This procedure reduced the interruption caused by a "back fire" to a second or so, at most, during which the metal scarcely cooled at all, while previously it often became very dark red, requiring some time to bring it again to the welding temperature. This cooling probably had a detrimental effect upon the strength of the welds.

27. *Strip G.*—In the tensile tests of specimens from strip G and in subsequent tests, instead of making an autographic diagram for the test of each specimen, the reading for ultimate strength was taken directly from the beam of the testing machine as usual, which effected a saving of time. The yield point for the welded specimens was not observed, as it appeared to depend entirely upon the yield point of the material outside the weld and to have no bearing upon the efficiency of the welds. Photographs of the specimens were also omitted as being unnecessary at this point in the work.

The allowance for creep in strip G was 0.4 in. The plates were beveled at 45° and four-strand No. 14 wire for filling used as for previous strips. A portion of these plates was used in demonstrating the rapidity of the modified methods of welding and was removed before making this weld. The surface of the weld was ground to obtain an approximately smooth surface. See Table 2 for data.

The average efficiency was 69.6 %, the highest 75.3% and the lowest 61.2%.

28. *Strip H.*—The allowance for creep was 0.45 in. The plates were beveled and ground after welding as for the previous strip. Instead, however, of using No. 14 wire for filling, a sample of $\frac{1}{8}$-in. soft iron wire supplied by the blowpipe manufacturers was used. See Table 2 for data. Apparently this $\frac{1}{8}$-in. wire did not make as strong a weld as the No. 14 used for the previous strip, but there were probably other conditions which affected the results.

The average efficiency was 50.6 %, the highest 58.9% and the lowest 41%.

29. *Strip R.*—The allowance for creep was 0.8 in., and three strands of No. 14 wire used for filling. Otherwise the conditions were the same as for the preceding strips. After welding the plates for about 12 in., it was found that the plates were separated by a gap which it was difficult to bridge with the filling material. Work was then stopped, and only the welded portion tested. See

Table 2 for data.

The average efficiency was 76.7 %, the highest 86.9% and the lowest 68.5%.

30. *Strip X.*—The allowance for creep was ½ in., otherwise conditions were the same as for the preceding strip. See Table 2 for data.

The average efficiency was 73.9 %, the highest 85.5% and the lowest 56.6 %.

TABLE 2.

RESULTS OF STRENGTH TESTS OF WELDS —FIRST SERIES.

Strip	Efficiency per cent			Rate of Welding ft. per hr.
	Av.	Max.	Min.	
A	69.3	90.7	47.7	1.47
B	68.0	79.0	56.3	....
C	74.3	90.5	52.7	....
D	64.5	79.0	52.7	1.00
E	69.2	80.5	54.6	....
F	66.9	74.9	55.0	2.80
U	54.0	74.0	35.1	....
Y	82.4	118.0	43.5	2.84
G	69.6	75.3	61.2	4.17
H	50.6	58.9	41.0	0.80
R	76.7	86.9	68.5	1.50
X	73.9	85.5	56.6	2.50

31. *Summary for First Series.—Grinding the Weld Surface.*— The necessity for removing the rough surface of the weld became very apparent when specimens from strip Y seemed to give over 100 % efficiency. A comparison of the range in efficiency for each section shows that upon the average ground specimens showed less variation than the unground. The unground strips are A, B, F, U, and Y, and their average range in efficiency, found by subtracting the lowest efficiency from the highest, is 39.8%. The ground sections are C, D, E, G, H, R, and X, and their average range is 22.2 %, only 56 % of range of the unground.

As explained for strip Y, when the weld was rough as left by the blowpipe, the constant tendency was to measure the least thickness near the point where a reading was to be taken. This, without doubt, frequently gave a sectional area less than the actual, and a consequently higher efficiency on the average for the unground specimens. The grinding introduced another factor into the problem whose influence upon the welds was unknown. If means were provided for milling the surfaces smooth, the temperature would probably never rise enough to cause any annealing effect. As care was taken in grinding to cool the specimen frequently, there is only a slight chance for annealing in these specimens.

32. *Consumption of Oxygen and Acetylene.*—The pressure gauges attached to both acetylene and oxygen tanks enabled the amount of gas consumed for each section to be computed. Readings of these gauges were taken during the welding of many strips. The amounts of acetylene and oxygen consumed were determined and compared with the average value for a No. 7 blowpipe given in the catalog of the blowpipe manufacturers. The measured average consumption of oxygen was 20.6 cu. ft. per hr. while 25 cu. ft. is given as the consumption in the catalog. The acetylene consumption was 22.7 cu. ft. per hr. and the catalog value is 15 cu. ft. The rather wide difference between the measured value and the catalog values and more especially the erratic fluctuations in the oxygen rate measured by gauge readings lead to the conclusion that while the pressure gauges are sufficiently accurate to determine the volume of gas contained in the tanks at any time, they are not sufficiently accurate (or sensitive) to determine the gas used for time intervals, say, of one hour. More accurate measurements were made in later tests. This subject is discussed in IV. Tests of Gases and Flame Regulation. The ratio of acetylene to total gas volume was also determined from the gauge readings and an average of 56.3 % found, which is much higher than the ratio of 37 % usually given, (1 volume of acetylene to 1.7 volume of oxygen). The ratio of the gas rates in the catalog is almost the same as this latter value, being 38.5 %. The wide fluctuations in the measured value of this ratio indicate that the tank gauge readings are wholly unreliable for determining this ratio or computing the quantity of gas used. Other means were therefore employed later.

33. *The Welding Rate.*—The rate of welding, of course, varies considerably with the skill of the workman and the conditions under which the work is done. The rates for the several strips are plotted in Fig. 12, and as might be expected, show an increase in speed as experience was gained.

In no case was the catalog value of 5 ft. per hr. reached, but it appears reasonable that an average, experienced workman could maintain that speed for several hours if not for the whole working

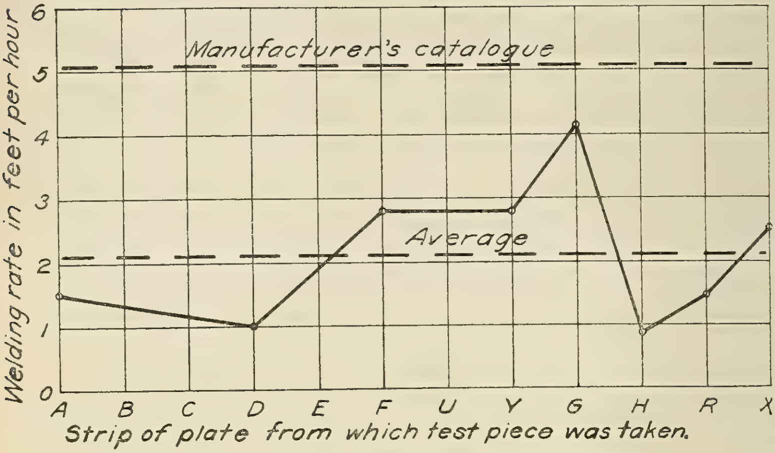
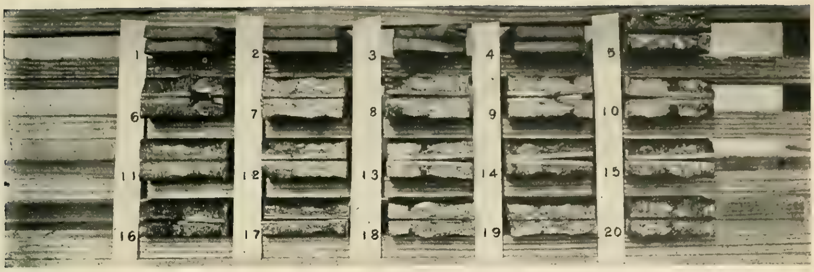


FIG. 12. RATE OF WELDING—FIRST SERIES.

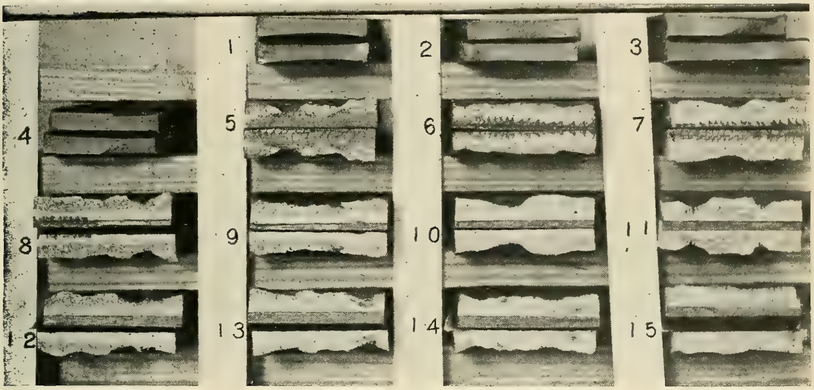
day. It should be noted that considerable instruction was received after strip Y was welded and that the method of working was changed considerably at that time. If the rate for strip G is excepted (possibly in error) the remaining strips, H, R, and X, show a return to about the original welding rate of one foot per hour with a much more rapid rise in the rate than was the case with the first strips. With continued practice, the catalog rate of 5 ft. per hr. would probably be reached.

It will also be noticed that the rate for strip Y, which was a butt weld, fused from both sides, is about the same as for strip F which was a beveled weld with wire filling. In both cases fusion occurred throughout the weld so that one method appears to permit about the same welding rate as the other.

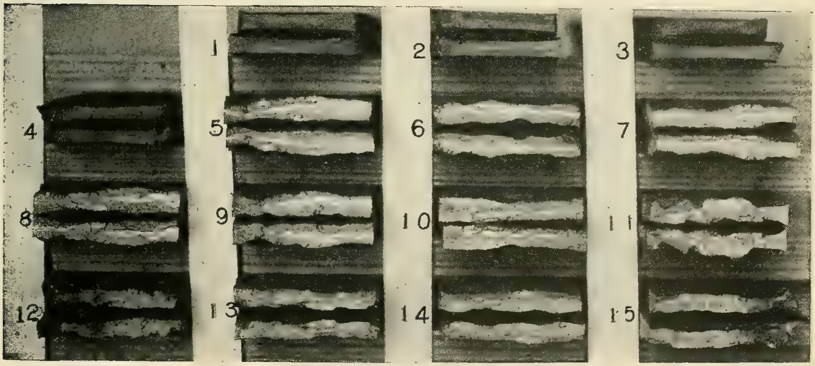
While too great reliance should not be placed upon these welding rates, either as to their accuracy or the ability of another workman to equal them, they do show that a moderate rate of welding, say, 2 to 3 ft. per hr. with $\frac{1}{4}$-in. steel plates, can be obtained with comparatively little practice. The total length of weld in these 12 specimens was about 24 ft. which at the average rate of welding of 2 ft. per hr. could be completed in 12 hours of blowpipe work. This tends to confirm the statement that some commercial shops train inexperienced men in two or three days to reasonable proficiency with the blowpipe and employ them upon their own work afterwards.



Strip A.



Strip U.



Strip Y.

Fig. 11. Fractured Surfaces of Test Specimens, (Specimens No. 1, 2, 3, and 4 are unwelded).

34. *Allowance for Creep.*—The values are shown in Table 3 for the allowance for creep in per cent of the length of the weld.

TABLE 3.

ALLOWANCE FOR CREEP OF WELDED JOINTS

Section	Approximate Length of Weld, inches	Allowance for Creep, inches	Per cent	Remarks
A	27	½	1.8	Rather small
B	27	⅝	2.3	Too much
C	20	½	2.5	
D	20	$\frac{9}{16}$	2.8	
E				
F	27	½	1.8	
U	20	None		Too small
Y	20	$\frac{5}{16}$	1.6	
G	20	0.4	2.0	
H	20	0.45	2.3	
R	27	0.8	3.0	Too much
X	20	½	2.5	

The average of those allowances which appeared to be satisfactory is 2.2 %; not much less than the 2.5 % recommended by the blowpipe manufacturers. If the allowance is too small, the thin edges of the plates crowd together more or less with no bad results, but if the edges fail to meet or nearly so, it is almost impossible to weld at a satisfactory rate.

35. *Properties of the Steel Plates.*—Of the strips welded, A, B, E, F, and R, were cut into specimens perpendicular to the direction of rolling, and strips C, D, U, Y, G, H, and X, were cut into specimens parallel to that direction. The material, as shown by averaging the tests of the unwelded specimens from each strip, had the properties shown in Table 4.

TABLE 4.

PROPERTIES OF STEEL PLATE—FIRST SERIES

	No. of Specimens	Yield Point lb. per sq. in	Ultimate lb. per sq. in.	Elongation in 6-inch gauge length per cent
Perpendicular to rolling	20	40 800	65 500	19.0*
Parallel to rolling	28	39 900	63 000	23.8*
Average		40 350	64 250	21.4

*These values include 12 specimens perpendicular to rolling and 16 specimens parallel to rolling.

No elongation was recorded for the remaining specimens of each group.

36. *Efficiency of Welds.*—The average efficiency of the welds for the strips perpendicular to rolling is 70 %, which compares favorably with that for the sections parallel to rolling, 67 %.

On account of the many variables in this series of tests, it may safely be concluded that this slight difference in efficiency is entirely accidental and that the direction of rolling, so far as these tests permit an opinion to be formed, has no influence upon the efficiency of the welds.

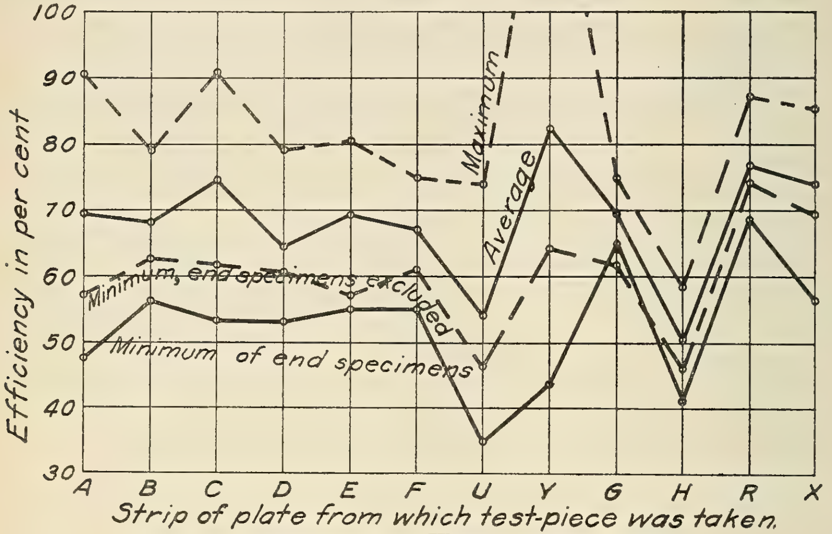


FIG. 13. EFFICIENCY OF WELDS—FIRST SERIES.

The efficiencies for each strip are plotted in Fig. 13, the maximum, minimum, and average being shown. To distinguish between end specimens and those from the body of the weld, the lowest efficiency of the end specimens and the lowest efficiency of inside specimens are shown separately. While the strength at the ends of the weld is markedly lower, this is not due entirely to the method of welding. In some specimens the width of the end specimens, at the weld, could not be accurately measured because one edge was not machined, and again, little effort was made when welding to obtain maximum strength at the ends.

Fig. 14 is a diagram showing the strength of the individual specimens of a representative strip.

A comparison of the strips shows that of the twelve strips, only in one (strip G) did the lowest efficiency occur at an inside specimen. Of the remainder, the minimum occurred at the beginning in three only (strips D, E, and H), while in the other eight it occurred at the end specimen, where work was stopped. In three of these (strips U, R, and X) the next lowest efficiency occurred at the beginning, while in the others it occurred at an inside specimen. Apparently any error in measuring the area of end specimens would act impartially either to raise or lower the efficiency so that this marked showing for low efficiencies at the beginning and end of the welds must be taken as evidence that such a tendency exists. While this appears reasonable at the beginning, where starting to weld with cold metal, it is not easily explained for the ends.

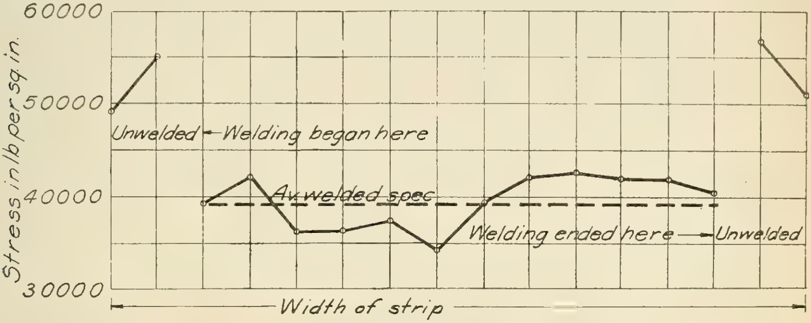


Fig. 14. Strength of Individual Specimens as Strip AB.

Inspection of Fig. 13 shows that there is little change in the average efficiency from A to F inclusive, but a marked decrease in the variation from the average is apparent, probably showing better workmanship and increased skill on the part of the operator.

Strips U and Y, it must be remembered, are butt welds, the first fused on one side only and the second on both sides. As previously explained, fusion of the metal in strip U did not take place for its entire thickness, which accounts for its low efficiency. The very high efficiency of strip Y, in which thorough fusion occurred, may be explained, possibly, by the fact that as the blowpipe flame was confined almost entirely to the surface of the weld the metal did not suffer the deterioration which occurred in the beveled welds in fusing in wire for filler. Possibly, also, the low efficiency of strip H can be explained on the same basis by noting the very slow rate of welding employed, less than one foot per hour.

Strips G to X, inclusive, were welded after instruction and the adoption of modified welding methods. As a result the efficiencies rose, say, from 70 % to 75 %.

The variation from the average efficiency, in these last strips, is small enough to show, with the somewhat increased average, that the newer method of working was an improvement over the old, but it seemed that some precaution might have been neglected which would increase the efficiencies considerably. Inspection of the fracture of specimens welded by the modified method showed a decrease in the amount of black or blue discoloration of the metal, although there was still more than could be wished. Possibly the effect of this discoloration is shown in the low efficiencies.

B. SECOND SERIES OF TESTS.

37. *Blowpipe.*—The work of the second series was a continuation of that of the first under somewhat altered conditions. An effort was made to determine the variables affecting the efficiency of the welds, with some success for the last few strips of the series.

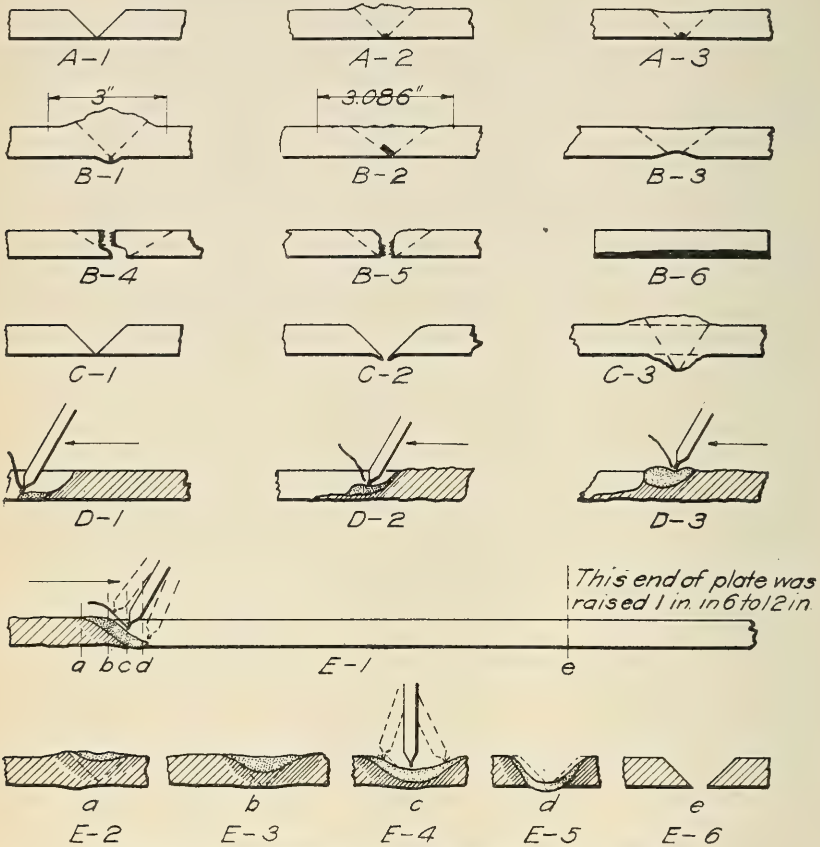
In place of the blowpipe used in the first series a recent form of the Fouché blowpipe was obtained which was provided with a number of interchangeable heads, in this case corresponding to the heads of blowpipes No. 3, 4, 5, 6, 7, and 8. The size best suited to the work could be quickly fitted to the blowpipe body, the result being an apparatus somewhat lighter than the design previously used but one operated in the same way. The general appearance of this blowpipe is shown in Fig. 3, (p. 12), the heads for it standing in a row at the right.

38. *Filling Wire, and Its Effect on Welds.*—Special wire, recommended by the blowpipe manufacturers, was obtained from John A. Roebling's Sons Company, 171 Lake Street, Chicago. This was designated by them as $\frac{1}{8}$-in. diameter, liquor finished, bright, annealed, genuine Norway iron wire. Tension tests of several samples gave the following results:

Ultimate strength	50 000 lb. per sq. in.
Yield point, about	31 000 lb. per sq. in.
Elongation in 10 in., per cent,	20
Reduction of area, per cent,	67

After being cut into lengths of about 6 ft., this wire was coiled, as shown in Fig. 3, so as to be readily held in the hand. Each coil was about sufficient for welding one strip of $\frac{1}{8}$-in. steel, 20 in. long. This wire melted readily and in general worked satisfactorily. The most noticeable difference between it and the No. 14 steel wire used up to this time was the absence of mill scale. If bent, the steel wire showed a coating of scale, or oxide, which flaked off. The iron wire, however, had been pickled or otherwise treated to give a clean metallic surface. When melted by the blowpipe, the steel wire showed a surface of moderate incandescence covered by irregular spots which were much brighter. While the general color appeared bright red through blue goggles, the spots seemed white hot. The red mass appeared quite firm, flowing reluctantly under the pressure of the blast from the blowpipe. The white material, on the other hand, seemed quite fluid and formed constantly changing figures on the red surface. Under the continued action of the blowpipe, it tended to gather into small globules. The impression formed as one watched it was that this material gradually decreased in amount under the blowpipe, but possibly its disappearance was due to its being driven on to comparatively cool metal where it was less visible. It seems probable that the red material was filler, fused without change, and the white hot material a film of oxide over it, as the behavior of each agreed with our general knowledge of these substances, especially that pure iron is melted with difficulty while the oxide melts at a much lower temperature. Possibly the oxide, if it is such, is reduced to metallic iron by the blowpipe. This would account for the disappearance of the oxide.

The steel wire, after each addition of material to the weld, showed half or two-thirds of the red area covered by the white, while the iron wire showed much less, possibly a quarter as much. In either case, some care was taken to continue the action of the blowpipe until the oxide had almost or entirely disappeared before adding more filler. Perhaps this was unnecessary, as the metal added may work down under the oxide; if, however, this does not occur, inclosing oxide in the weld must, necessarily, reduce its strength and efficiency. Possibly, dark spots in the weld after rupture are inclosed oxide.



This end of plate was raised 1 in. in 6 to 12 in.

FIG. 15. PROGRESS OF WELDING—SECOND SERIES.

39. *Material and Preparation of Specimens.*—Instead of the $\frac{1}{4}$-in. plates used for the first series, similar sheets from the same firm were obtained which were $\frac{1}{8}$-in. in thickness. Plates of this thickness seem better suited for practice welding and experimenting than either thicker or thinner ones. Each plate was divided into strips, as shown in Fig. 5 (b), so that all specimens lay with their longest dimension parallel to the direction of rolling. The strips were cut as for the first series, except that a sharp power shear was used instead of the cutting-off tool.

All strips were beveled at 45° as shown at A-1, Fig. 15. This was done on a dry emery wheel as the amount of metal to be removed was not large. Each section was clamped, as usual, and welded by fusing in a $\frac{1}{8}$-in. iron wire, using the No. 5 head fitted to the blowpipe.

The pressure under which oxygen was supplied to the blowpipe was 12 lb. per sq. in. The acetylene pressure averaged 11.8 in. of water and varied from 11.5 to 12.75 in. As slight variations in these pressures probably had little or no effect on the flame regulation or the welds, they need little consideration.

A cross-section through the weld is shown at A-2, Fig. 15. As is the case with all the sketches in Fig. 15, an attempt is made to show the general features of the weld under discussion, not to represent them accurately to scale, which would be difficult if not impossible. Many are exaggerations, more or less crude, of the phenomena they are intended to illustrate.

All specimens were cut from the strips with the power hack saw, as before, and the surface of the weld ground, as shown at A-3, top and bottom, on a dry emery wheel, to give a reasonably smooth surface. In many cases the thickness through the center of the weld was slightly less than that of the plate.

40. *Manipulation.*—For all of the strips of the second series the welding process used for the last of the first series was employed, the pool system of welding used at first (described on page 18) having been discarded. The difficulties involved in the pool system and in working away from the operator can better be understood by reference to D, Fig. 15. In the diagram, comparatively cool metal (black hot) is represented by coarse cross hatching, or is left unshaded; metal heated to redness, by close cross hatching, and molten metal is represented by a dotted surface. The arrows indicate the direction in which the weld is progressing. In the pool method the bottom of the groove was first welded for a short distance (See D-1) by melting down the sides of the groove (see E-5) and adding some filler. The thickness was then increased by a pool (See D-2) to the required thickness of the plates (see D-3). Working in this way it was somewhat difficult to prevent the filler cooling on metal imperfectly fused.

The method used for the welding of the second series is shown in Fig. 15. A longitudinal section along the weld is shown at E-1, and cross sections through several points at E-2, E-3, E-4, E-5, and E-6. The weld was built up by means of additions of melted filling wire at the front of the work, regularly, so that the surface advanced along the groove approximately parallel to itself. The bottom of the groove was closed by material from the sides of the groove and from the filling wire, (see E-5); then the thickness of metal was gradually increased until somewhat greater than that of the surrounding plates. As each drop of melted filler reached its place, the blowpipe was directed against it until it spread out over the molten material below and lost its outline. The oxide on the surface was driven off before more filler was added. Usually the distance from the flame to the metal was 50% to 100% of the length of the first cone.

41. *Strip AB.*—Only one clamp was used for this strip and it was applied at the raised end opposite that where welding started. The thin plates sagged, one more than the other in places, which made an offset in the weld, reducing its area.

The fractures showed a rather dead or dull gray surface, slightly spongy, with small dark spots at intervals. See Table 5 for data.

The average efficiency was 72.1%, the highest 77.9% and the lowest 62.5 %.

42. *Strip AC.*—Both clamps were used as in the first series, preventing sagging somewhat. On account of the small allowance for creep, the plates overlapped so that satisfactory work was impossible. The weld was carried within about two inches of the end of the seam but only about the first 13 in. was cut into specimens. Of these, only the following three, No. 10, 11, and 12, were welded on both sides in an attempt to fill up the angle due to the offset.

The fractures were similar to those for strip AB. See Table 5 for data. A rise in strength was noted for specimens No. 9, 10, and 11, due probably to welding both sides of the plates. Specimen No. 11 broke first outside the weld; then, when retested, in the weld. The greater load was used in computing the stress on the cross sectional area of the weld, and this applies to all specimens of this series which were retested to cause rupture in the weld.

The average efficiency was 69.1 %, the highest 82.0% and the lowest 54.4 %.

43. *Strip AD.*—Satisfactory allowance for creep ($\frac{1}{2}$ inch) was made for this strip and the weld completed. Some offset occurred due to sagging of the plates, but they were welded from one side only.

The fractures showed some dark spots in the dull gray, spongy surface and also a few crystalline spots at intervals. See Table 5 for data. A rather remarkable increase occurred in strength as work progressed along the weld.

The average efficiency was 78.2 %, the highest 94.8 % and the lowest 72.0 %.

44. *Strip AE.*—To prevent sagging of the plates when heated, the clamps previously used were bolted up on pipe spacers, as shown in Fig. 3. These spacers held the lower T-sections of each clamp in a definite relation to each other. The plates were then clamped with the clamps parallel to the weld. This arrangement kept the plate surfaces nearly in the same plane—an important matter with thin plates—so that the weld has nearly the cross sectional area of the rest of the specimen.

The fractures showed generally a clear gray surface with a slight spongy appearance. There were very few dark spots. See Table 5 for data. Great strength was shown by specimens No. 8, 9, 10, and 11. This is partly explained by the fact that all others had a band of metal about $\frac{1}{32}$ in. wide at the bottom of the weld which appeared to be poorly welded. Possibly fusion did not take place there.

The average efficiency was 75.6 %, the highest 90.0 and the lowest 59.9 %.

45. *Strip AF.*—The clamp used for strip AE was improved by welding the spacers and bolts to the T-sections, making the clamp stiffer. The upper T's were then removed and the bearing surfaces, for the plates, finished in the shaper. This assisted greatly in bringing the plate surfaces into the same plane and avoiding offset in the weld. This clamp was used for all subsequent work for this series.

The fractures showed a bright surface with almost no dark spots. While it tended toward dull gray, it was not spongy. Specimens No. 6 to 10, inclusive, had a gray surface with crystalline spots while No. 11 to 16, inclusive, were largely crystalline. Specimen No. 17 showed a dark band across the weld. See Table 5 for data. An increase in strength was shown by specimens with crystalline fracture.

The average efficiency was 72.0 %, the highest 87.4 % and the lowest 44.8 %.

46. *Strip AG.*—As the strength of the welds up to this time had shown little increase, the molten metal for strip AG was hammered frequently as it was put into place. A small riveting hammer was used, having a handle 11 in. long, and a head weighing 11.5 ounces. After extending the weld about $\frac{1}{4}$ in., 10 to 15 light blows, (2 in. stroke) were delivered rapidly upon the sloping surface at the end of the weld. During this time the metal usually became very dull red and required some time to bring it to the fusion temperature again.

The fractures showed no crystals but rather a dull gray spongy surface, covered by many dark spots. These, perhaps, aggregated a quarter of the total area. See Table 5 for data. The wide and erratic fluctuations in strength lead to the conclusion that alternate hammering and welding do not produce uniform work. The fact that the average efficiency was lower than for any strip so far in this series also throws doubt upon its value. It is difficult to see how hammering can increase the density of metal which is immediately afterwards heated to fusion to continue the weld. The amount of work required of the operator is largely increased, as well as the time.

The average efficiency was 64.4 %, the highest 76.8 % and the lowest 50.9 %.

47. *Strip AH.*—A gasoline torch was used to preheat the beveled edges of the specimens of strip AH. Its flame was directed against the seam, from below, an inch or two in advance of the end of the weld. This did not interfere with the welding as the blowpipe was used from above as usual. The torch supplied enough heat to bring the bottom of the groove to redness, which reduced, considerably, the time required to melt the metal. The preheating also noticeably increased the allowable freedom in using the blowpipe. It could be swung over a greater area of weld and also be held at a greater distance; moreover, the filler flowed quickly into the weld. Though the welding rate is lowered, rather than raised, delays due to stopping the work entirely are included so that the rate, as given, is incorrect. A rough estimate would put the rate of welding for preheated plates about twice that for cold ones. The rapidity and ease with which the filler united with the weld would lead one to think, also, that great strength should result.

Work progressed continuously until specimens No. 5 to 11, inclusive, had been welded, then there was a delay of a minute or more to pump up the pressure in the gasoline tank of the torch. Specimens No. 12, 13, and 14, were next welded; then the gasoline became exhausted, making it necessary to complete the weld without preheating. This portion includes specimens 15,16,and 17.

It had been noticed that many of the preceding welds showed after rupture a narrow strip just at the bottom of the groove which apparently was poorly welded. This defect is indicated in A-3, Fig. 15, by a black spot which the usual grinding of the weld surface did not remove. After rupture, the fracture presented the appearance shown in B-6, which is a cross section of the specimen. The band of poor welding, shown in solid black, is along the bottom of the weld. It varies somewhat in thickness; above the poorly welded part is gray or crystalline material which had evidently been melted. To determine the strength of welds, from which this defect is removed, specimens No. 7, 10, 13, and 16 were grooved with a half round file along the bottom of the weld, as shown in B-3. The fractures for these showed no poorly welded band. The specimens showed a rather spongy dull gray surface with a large number of dark spots. An exception to this was specimen No. 15, which was almost entirely crystalline with no dark spots.

See Table 5 for general data for strip AH. As nearly as could be determined, the interruptions to the work occurred at specimens No. 11 and 14. These were noticeably low in strength. The specimens grooved to remove imperfect welding, No. 7, 10, 13, and 16, on the other hand, showed remarkable strength compared with the others. The high values for No. 10 and 13 may be due more to this fact than to the preheating. Evidently, this poorly welded portion of the specimens has been an important factor in causing low efficiencies, especially in these thin plates which had generally been left about $\frac{1}{32}$ in. thick at the beveled edge to prevent the blowpipe readily melting through the bottom of the groove. It is peculiar that specimen No. 15, welded without preheating, showed a good crystalline fracture while all preheated specimens had poor ones.

The average efficiency was 69.5%, the highest 88.0% and the lowest 56.5%.

48. *Strip AJ.*—This strip was welded before the results for the previous one were available, so no precautions were taken to avoid poor welding at the bottom of the groove. The weld was built up, perhaps $\frac{1}{16}$ in., above the plate surface, as shown in B-1, Fig. 15, (p.38). After cutting the specimens, a 3-in. gauge length was laid off and prick-punched, having the weld in the middle. These specimens were then heated in a forge and drawn down on an anvil to a uniform cross section with a hand hammer. Two heats were required for this usually. The specimens were allowed to cool slowly. They showed an average elongation (see B-2) in the 3 in., due to forging, of 0.086 in. The greatest was 0.11 in. and the least 0.07 in. The surfaces of the weld were then ground smooth.

When tested, the poorly welded portion at the bottom, shown at B-1, appeared to have been drawn out in forging, (see B-2), causing a fracture similar to that shown at B-4. Specimens No. 12, 13, and 17, broke in this way, about half the thickness of the last being unwelded.

The first three specimens showed rather poor fractures but the remainder were better. There were no dark spots. Specimen No. 15 showed remarkable ductility in the material actually in the weld, B-5, and a good fine grained fracture. The same indications of ductility were shown in a lower degree by other specimens also. The average per cent elongation, 12.5, was high compared with previous welded specimens which average about 3 % in 6 inches.

See Table 5 for data. While the results are somewhat erratic, forging is evidently of value in increasing the ductility as well as the strength.

The average efficiency was 85.4%, the highest 124.6 % and the lowest 54.1%.

49. *Strip AI.*—To allow the poorly welded portion at the bottom of the weld to be ground away, leaving in the test weld only material which had been thoroughly fused, the plate edges, C-1, Fig. 15, were bent downward from $\frac{1}{32}$ in. to $\frac{1}{16}$ in., as in C-2, by hammering over the edge of an anvil. The weld when completed was much like C-3, and was then ground about as shown by the horizontal dotted lines.

The fracture showed very few dark spots on a gray surface and no poorly welded portion. Specimens No. 11, 12, and 15, showed a crystalline surface.

See Table 5 for data. The strength of this strip showed quite conclusively that lack of thorough welding was largely responsible for previous poor results.

The average efficiency was 86.6 %, the highest 104.6 % and the lowest 65.2%.

50. *Strip AK.*—To determine the effect of improper flame regulation this strip was welded with an excess of oxygen. The blowpipe flame was shortened by reducing the amount of acetylene until about half its length when properly regulated. This caused frequent "back firing", as the short flame made it necessary to work with the blowpipe close to the metal.

The method of working was the same as for strip AI, including thickening the weld by bending down the beveled plate edges. The fractures were much like those for the preceding strip. See Table 5 for data.

The average efficiency was 84.7 %, the highest 100.5 % and the lowest 72.5 %.

51. *Strip AL.*—This strip was welded in the same way as the last, including the thickened weld, except that an excess of acetylene was supplied. The second cone was, as nearly as could be estimated, 50 % longer than the first cone. As the second cone had a very fine point, its exact length was hard to determine.

The fractures were much like those for the preceding strip. See Table 5 for data.

The average efficiency was 83.1 %, the highest 92.0 % and the lowest 72.1%.

TABLE 5.

RESULTS OF STRENGTH TESTS OF WELDS —SECOND SERIES.

Strip	Efficiency per cent			Rate of Welding ft. per hr.
	Av.	Max.	Min.	
AB	72.1	77.9	62.5	1.32
AC	69.1	82.0	54.4	0.75
AD	78.2	94.8	72.0	1.55
AE	75.6	90.0	59.9	1 75
AF	72.0	87.4	44.8	1.51
AG	64.4	76.8	50.9	1.39
AH	69.5	88.0	56.5	0.92
AJ	85.4	124.6	54.1	1.17
AI	86.6	104.6	65.2	1.03
AK	84.7	100.5	72.5	0.90
AL	83.1	92.0	72.1	1.44

52. *Properties of Steel Plates.*—The unwelded specimens from these plates had sheared edges. Table 6 shows the average strength of specimen with sheared edges and with machined edges. The following method was used to compute the ultimate strength of a machined edge specimen from one having sheared edges. Two of the four specimens, for a number of the sections, were machined on the edges.

TABLE 6.

PROPERTIES OF STEEL PLATE—SECOND SERIES

	Sheared Specimen	Machined Specimen
Average ultimate stress, lb. per sq. in..	53 100	56 400
Range of variation from the average, per cent,	11.3	6
Average width, inches,	1.619	1.313
Average elongation in 6 in., per cent,	9	18

A study of Table 6 shows that, if the width of a sheared specimen is reduced 40% of the thickness of the plate for each sheared edge and this width used in computing the ultimate stress, it will agree closely with the average for a specimen having machined edges.

The same result may be obtained if the widths of specimens are nearly uniform as in this work by increasing the stress by a proper percentage; in this case six per cent. While this approximation saved much time in preparing specimens it is not to be recommended for work requiring a high degree of accuracy. In this case, however, it is believed that the data, upon which the correction is based, are taken from enough specimens to be reliable.

53. *Slope of Plates.*—During the process of welding all strips were sloped upward in the direction of welding about 1 inch in 7.7 inches. The greatest slope was 1 in 5, and the least 1 in 19. The exact amount is a matter of little consequence and will depend upon the preference of the operator and the conditions under which the work is done.

54. *Creep of Plates.*—The allowance for creep averaged 0.5 in. which was 2.56 % of the length of the weld. Two strips were welded satisfactorily with an allowance of $\frac{7}{16}$ in. and two with $\frac{9}{16}$

in. An attempt to weld a strip (AC) with only $\frac{3}{8}$ in. caused overlapping of the plates.

55. *Rate of Welding.*—The average rate of welding, 1.24 ft. per hr., for this series, seems very low when compared with the catalog value of 15 ft. per hr. Fig 16 shows the rates for all strips. The very low value of strip AC was due, doubtless, to the overlapping of the plates. Hammering the weld for strip AG and delays in working the torch when preheating strip AH lowered the rate for both these strips. The very short flame and frequent "back firing" also noticeably lowered the rate for strip AK, but there is no apparent reason why the remaining values should not be higher. Possibly the operator did not extend the weld as fast as circumstances permitted. If the only result was the low welding rate, it is of small consequence, but possibly the prolonged action of the blowpipe upon the metal was detrimental, causing lower efficiencies than would be found with a higher welding rate. The lower rates for the thickened welds, AI, AK, and AL, were doubtless due to the greater amount of filler to be added and the radiation from the greater mass of metal. Even for the first sections, the size larger blowpipe, No. 6, might have produced better results.

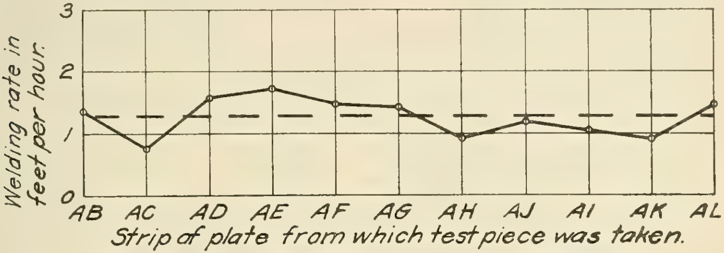


FIG. 16. RATE OF WELDING—SECOND SERIES.

56. *Hammering, Preheating, and Forging.*—While the results are far from conclusive, they tend to show that hammering the weld during the blowpipe operation is laborious and detrimental rather then beneficial.

Preheating undoubtedly increased the welding rate and so lowers the cost, but in so far as these results show, has little effect on the strength of the weld.

Forging produced a decided increase in the strength of the welds and also in the ductility of the fused metal. Apparently the increase in efficiency is about 10 %.

The average efficiencies and also the range of efficiency is shown in Fig. 17. Minimum efficiencies are shown both for end specimens and for inside specimens.

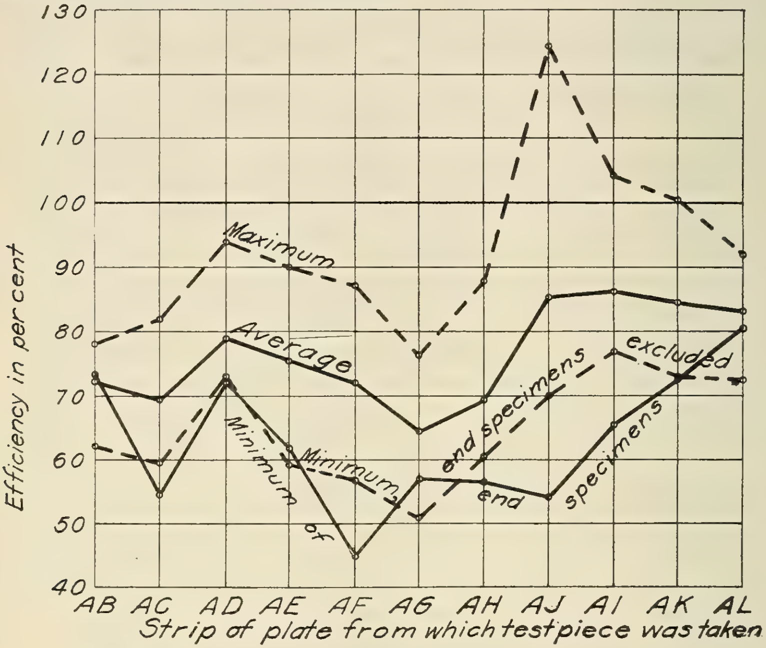


FIG. 17. EFFICIENCY OF WELDS —SECOND SERIES

57. *Effect of Thorough Fusion.*—The most important results of this series are obtained from the last three strips in which thorough fusion took place throughout the test weld. The average efficiencies were the highest obtained in these tests. The high average efficiency for strip AI, 86.6 %, confirmed as it is by the values for strips AK and AL, may be expected to be fairly representative of welds in ⅛-in. steel when fusion has occurred throughout the weld.

58. *Effect of Flame Regulation.*—The variation of efficiency with the flame regulation is seen in Fig. 18. If it is remembered that the excess oxygen flame was difficult to manipulate, and that the second cone of excess acetylene flame was very conspicuous, it seems fair to assume that an ordinarily skillful workman would in practice have only about half the variations, either way, shown

here. If this were true, his blowpipe flame regulation would always lie between that shown in Fig. 4 (b) and that in Fig. 4 (d) with very slight corresponding variation in the efficiency of the welds.

The decrease in efficiency due to the excess oxygen flame was only 1.9 % and for the excess acetylene flame 3.5 %. There seems to be no excuse for a greater variation in commercial work due to improper regulation.

For comparison the results for strip D of the first series are given also in Fig. 18. When it is remembered that thorough fusion did not take place throughout this weld, the slight rise in efficiency for the excess oxygen flame is not surprising. Upon the whole the results for strip D confirm the results found for the second series very well.

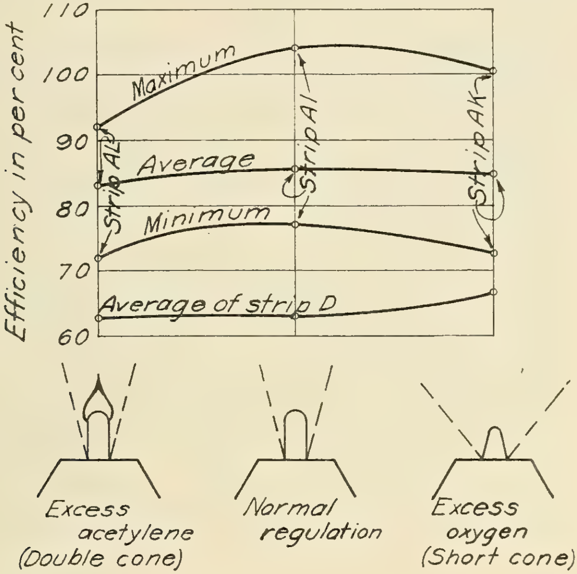


FIG. 18. EFFECT OF VARIATION OF FLAME REGULATION ON EFFICIENCY OF WELDS.

It would seem that a considerable variation from the normal flame regulation may be allowed without danger of greatly reducing the efficiency of the weld.

IV. TESTS OF GASES AND FLAME REGULATION.

59. *Sampling Gases.*—As varying the flame regulation seemed to have little effect upon the welds in the second series, interest was renewed in the proportion of acetylene in the discharged gas and the variation in this amount for visible changes in the flame. Apparently the only way to determine the proportion of acetylene was to light the blowpipe and secure the desired regulation, then, after extinguishing the flame, to collect a sample of the discharged gases and make a chemical analysis.

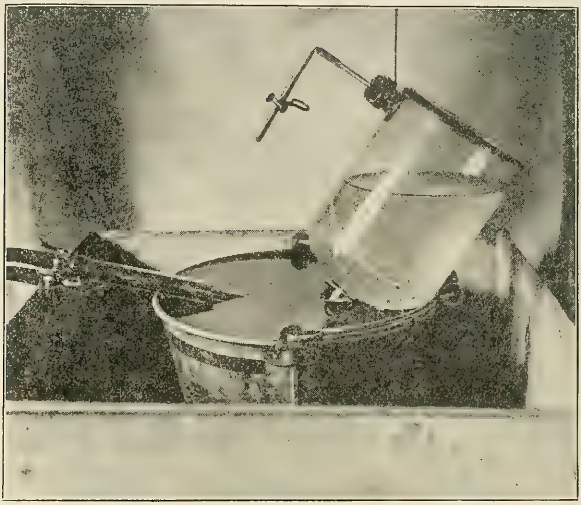


FIG. 19. APPARATUS FOR SAMPLING GASES.

The apparatus for collecting samples of gas is shown in Fig. 19. A bottle was suspended by a slip noose at a fixed height for all samples. With the bottle placed mouth downward full of water and with the mouth of the bottle submerged under the surface of water in a pail, the blowpipe was thrust into the neck of the bottle and the discharged gas collected. This arrangement maintained atmospheric pressure upon the blowpipe tip so that the rates and proportions of the gases were the same as for the flame. Care was taken to keep the blowpipe tip on a level with the water outside the bottle. Probably the greatest variation from the proper level was a quarter inch, or possibly half an inch. The edge of the pail acted as a weir to maintain a constant water level outside the bottle. The time required to fill the bottle was observed. As the time was taken with an ordinary watch the greatest error may have been a second or two.

60. *Flame Regulation.*—For the first twelve gas samples taken the flame was extinguished by closing the tip for an instant, but back firing sometimes resulted, rendering the sample worthless. For all subsequent samples the acetylene cock on the hydraulic back pressure valve was closed to extinguish the flame, then reopened and the gas sample taken. By this method the positions of the cocks on the blowpipe, used in regulating the flame, were unchanged. After obtaining the sample the blowpipe was again lighted to prove that the regulation had not altered.

Three characteristic flame appearances were selected for this work, similar to those previously used (see p.13). In using the oxacetylene blowpipe the best results are usually obtained with a flame showing a single cone of the largest size possible. This regulation is termed "O K" or normal regulation. For this regulation slight variations in appearance were purposely introduced to determine their effect. Any sample of gas obtained with "O K" regulation showed a flame like that in Fig. 4 (c), or in some cases with a cone slightly shorter than that shown in Fig. 4 (c). So far as the results of the analyses show, the slight shortening of the cone was entirely inappreciable with the experimental errors which occurred in this work.

The regulation in which the length of the flame was 50% longer than when properly regulated is here termed the double-cone regulation, and is shown in Fig. 4 (b) fairly accurately. This regulation was used to determine the effect of excess-acetylene flame. For any flame there is some difference between its appearance in a photograph and when seen directly. It also makes considerable difference whether or not blue goggles are used. Although the outer cone flickered considerably at times, care was always taken to obtain as nearly as possible the appearance shown.

The excess-oxygen regulation obtained by reducing the amount of acetylene until the length of the first cone was one-half to two-thirds that when normally regulated, as is shown in Fig. 4 (d), was used to determine the effect of an excess of oxygen. Usually half-length of cone was obtained only with difficulty due to frequent "back fires". This regulation is termed short-cone regulation. Generally a scale placed parallel and close to the flame was used to assist in regulation.

For all these regulations, the oxygen cock on the blowpipe was full-open and the desired flame appearance was secured by adjusting the acetylene cock. In a few cases this latter was also full-open.

61. *Chemical Analysis of Gases.*—No attempt was made to determine the impurities in either oxygen or acetylene, simply the proportion of each with reasonable accuracy. The apparatus used is shown in Fig. 20. The gas sample was in bottle A, from which a measured volume was transferred to the graduated tube B. The acetylene in the mixture was absorbed by fuming sulphuric acid in C, and the remaining acid fumes by caustic potash in D. The volume remaining in the tube was then noted. This consisted of oxygen and the impurities contained in both the oxygen and acetylene.

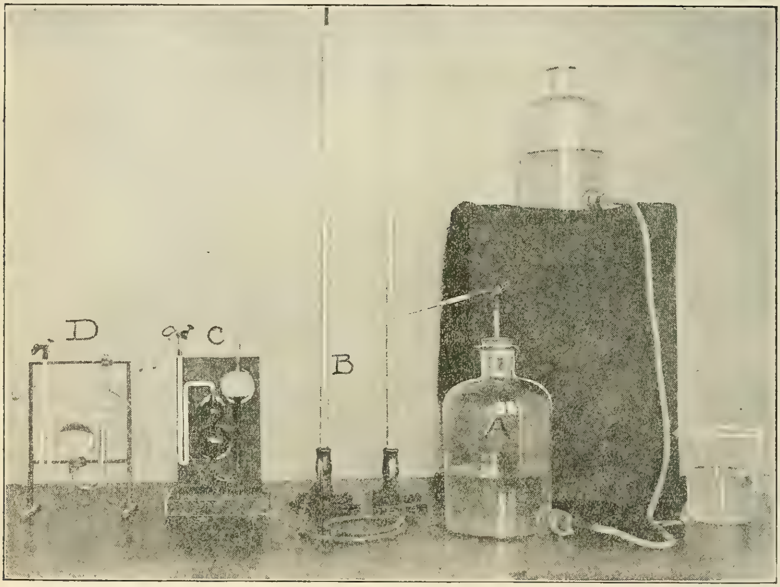


FIG. 20. APPARATUS FOR THE ANALYSIS OF GASES.

The data for representative samples are given in Table 7, which is largely self-explanatory. The volume of acetylene was, obviously, the difference between the initial and final volumes; but

TABLE 7.

Sample Gas Analyses for Oxyacetylene Blowpipe.

Sample No.	Blowpipe No.	Flame Regulation	Pressure of Acetylene in inches of water	Oxygen Pressure lb. per sq. in.	Initial Volume, cc	Final Volume, cc	Acetylene Volume, cc (A)	Oxygen Volume, cc (O)	Corrected Volume, cc (T)	Per cent Acetylene ($\frac{A}{T}$)	Per cent Oxygen ($\frac{O}{T}$)	Ratio of Oxygen to Acetylene	Bottle filled in seconds	Gas Rate, cu. ft. per hr.	Acetylene Rate, cu. ft. per hr.	Oxygen Rate, cu. ft. per hr.
1	5	OK	12	12	100.0	57.85	42.15	56.0	98.15	42.9	57.1	1.33				
					100.0	57.4	42.6	55.8	98.2	43.4	56.6	1.31				
									Av.	43.2	56.8	1.32				
2	5	OK	13⅜	0	99.9	1.1	98.8			99.0			100	5.34	5.34	
					99.7	1.3	98.4			98.6						
					98.3	1.0	97.3			99.0						
3	5	OK	13¾	0	86.1	2.0	84.1			97.5			100	5.87	5.87	
					95.8	2.4	93.4									
4	5	F	13¼	12	96.0	44.7	51.3	43.4	94.7	54.1	45.9	.846	35	16.8	8.96	7.83
					91.5	43.4	48.1	42.0	90.1	53.4	46.6	.873				
					92.2	43.7	48.5	42.4	90.9	53.4	46.6	.875				
					93.3	45.0	48.3	43.6	91.9	52.5	47.5	.905				
									Av.	53.4	46.6	0.875				
5	5	D	13⅜	12	92.1	50.8	41.3	49.3	90.6	45.5	54.5	1.19	43	13.65	6.14	7.51
					90.1	50.3	39.8	48.7	88.5	45.0	55.0	1.22				
					93.0	52.5	40.5	51.0	91.5	44.3	55.7	1.26				
					89.4	58.1	31.3	56.4	87.7	35.7*	64.3*	1.80*				
					96.1	62.7	33.4	60.9	94.3	35.4*	64.6*	1.82*				
									Av.	45.0	55.0	1.22				

F, Both acetylene and oxygen cocks full open.
D, Double-cone regulation.
*, Results omitted from average.

the oxygen volume was not so easily obtained. To make the results as accurate as possible, the impurities of both the gases were estimated and proper allowance made for them. The oxygen is guaranteed to be 95% pure and Dr. Jesse found by analyzing samples from a number of cylinders, none of which, however, was used for this work, that the highest per cent of oxygen was 98 and the lowest 96. It was, therefore, assumed that this oxygen was 97% pure. The first fifteen samples were from one oxygen tank and the remainder from another.

The acetylene manufacturers claim absolute purity for their gas. Attempts to analyze acetylene samples showed 99% for the first and a lower value for the second. Difficulty was found in manipulating the gas, due to the almost complete absorption, so that they seem to show only that the impurities could not exceed one per cent. Due to the lack of other definite information the statement of the manufacturers was accepted and the assumption made that the entire final volume was from the oxygen tank, 97% of which was oxygen. The sum of the acetylene and oxygen volumes gave the corrected volume upon which to base the oxygen and acetylene percentages as indicated in the column headings.

62. *Gas Consumption.*—The time required to fill the bottle varied from 110 to 15 seconds. If there was a possible error of 2 seconds in these readings the resulting gas rates would be in error 1.8 and 13.3%, respectively. Due to this fact, the oxygen impurities were ignored and the total gas rate apportioned between the oxygen and acetylene by the average percentage of each for the sample.

To determine the volume of gas collected, the bottle was weighed when full of water and again when bubbles escaped from the mouth. This was done by closing the mouth with the palm of the hand and weighing after removing the bottle from the pail. The gross weight was 6380 grams and the tare 1759 grams, making a net weight of 4621 grams. Neglecting temperature changes, this numerical value also measured the gas volume in cubic centimeters. The rate in cubic centimeters per second was then multiplied by the reduction factor 0.127 to obtain the gas rate in cubic feet per hour.

63. *Regulation Curves.*—The percentage of acetylene was chosen to measure the flame regulation, because it was the acetylene which was varied directly, although the ratio of oxygen to

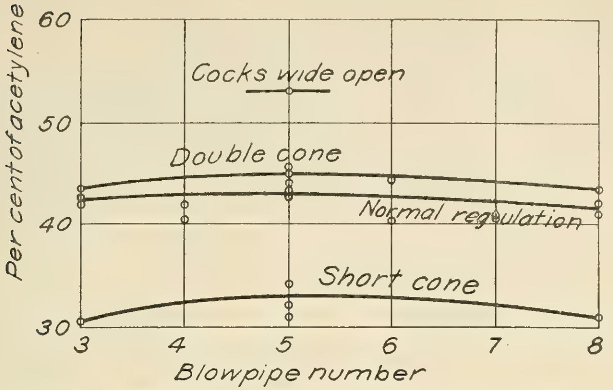


FIG. 21. EFFECT OF FLAME REGULATION ON THE COMPOSITION OF GASES.

acetylene might as well have been used. The average percentage for each sample is plotted in Fig. 21.

64. *Gas Consumption Curves.*—In a similar manner, the values for total gas consumption, or rate, and for acetylene were plotted in Fig. 22. In Fig. 22 are also plotted the rates given by the manufacturers of the blowpipe in their catalog.

65. *Oxygen Pressure and Regulation.*— For the previous graphs values are plotted only for samples taken with normal

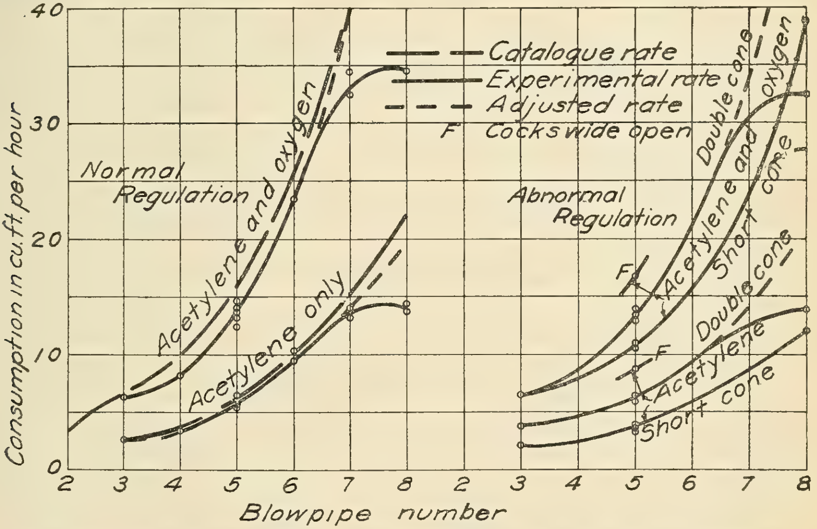


FIG. 22. GAS COMPOSITION WITH BLOWPIPES OF DIFFERENT SIZES.

oxygen pressure on the blowpipe. These pressures were as follows:

Blowpipe Number	Oxygen Pressure lb. per sq. in.
3	10
4	11
5	12
6	14
7	16
8	19

The only exceptions were for blowpipes 7 and 8 for which normal regulation could not be obtained, as is explained later. The acetylene was supplied under a practically constant pressure of about one foot of water for all series.

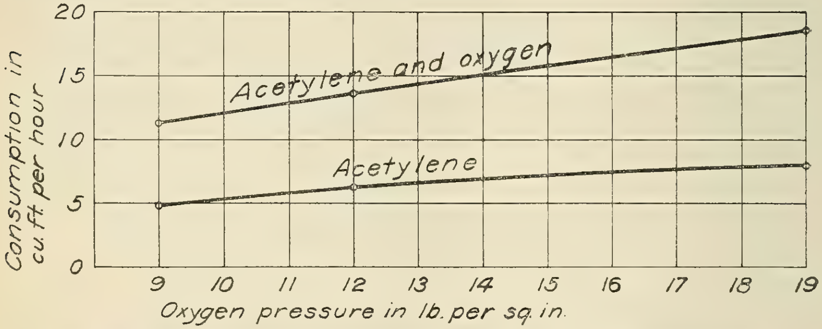


FIG. 23. EFFECT OF OXYGEN PRESSURE ON GAS CONSUMPTION.

The effect of varying the oxygen pressure upon the regulation and gas rates is shown in Fig. 23. Blowpipe 5 was used and normal regulation carefully maintained in each case. The values for the normal pressure (12 lb. per sq. in.) were those previously used.

The maximum and minimum pressures were fixed by the facts that trial proved that the flame "blew out" or was extinguished if the pressure was raised to 24 lb. per sq. in., making 19 lb. per sq. in. about the highest which gave a satisfactory flame and that the pressure gauge used did not read below 9 lb.

66. *Cost of Welding.*—The data given in the manufacturer's catalog for gas consumption for different blowpipes do not differ greatly from the data obtained in the tests herein described. It would seem then that the catalog data may be utilized to give the

cost of welds sufficiently accurately to allow comparisons to be made. Fig. 24 has been made up from these data. The cost of acetylene was taken as 1 cent per cu. ft.; of oxygen as 3 cents per cu. ft.; and of labor as 30 cents per hour. The curves need little explanation. The costs as shown by Fig. 24 are probably rather high, and lower costs may be obtained in practice. This applies in general to both the labor and gas items.

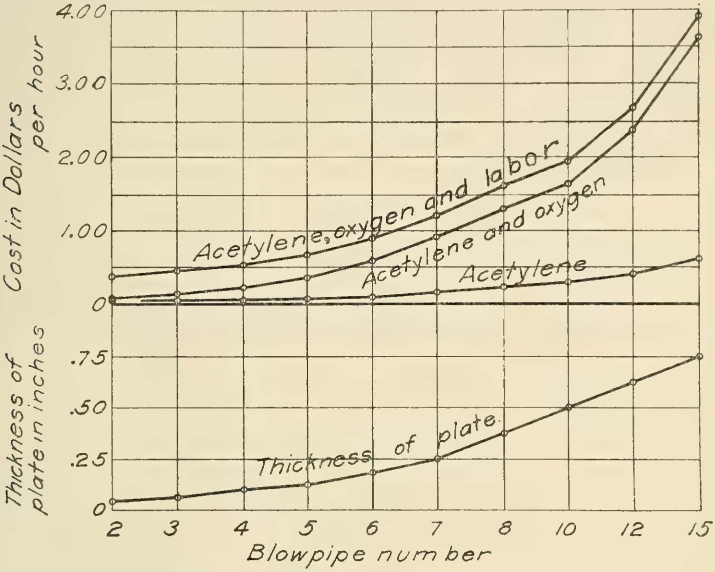


FIG. 24. COST OF OPERATION OF BLOWPIPES OF DIFFERENT SIZES.

67. *Discussion of Results.—Flame Regulation.*—The most striking feature of this work is the remarkable characteristic appearance of the blowpipe flame and its sensitiveness in showing changes in regulation. It seems safe to conclude that a change in the amount of acetylene of one per cent of the gas volume could be detected by the change in the appearance of the flame, provided, of course, that this occurred at or near the normal regulation. The flame is much more sensitive, also, in indicating excess acetylene than excess oxygen, so that a slight feathery flame tip is preferable to a slight or incipient shortening. All sizes of blowpipe appear to have practically the same regulation curve.

The proportion of acetylene for all sizes of blowpipes at normal regulation averages 42% in the tests. This is a ratio of 1.38 volumes of oxygen to one of acetylene, which is much less than the ratio 1.7 usually given. The ratio computed from the catalog rates for blowpipes 2 to 8, inclusive, is 1.61 to 1. The ratio of oxygen to acetylene does not seem to correspond to any definite stage in the oxidation of the acetylene gas. It does, however, appear to be a definite property of oxyacetylene blowpipe flames. As the gases are mixed before issuing from the blowpipe tip, it would appear to be a property entirely independent of the particular style or make of blowpipe. It may be noted that one manufacturer states that for their blowpipe the ratio of 1.28 oxygen to 1 of acetylene has been "adopted". Also that this is nearly the ratio fixed by the Academy of Science, France, which selected 1.30 to 1. The latter two values are nearer to those found by the tests than that given by the manufacturers and may be more nearly correct, but it would be interesting to know how the ratios were established. It would also be of interest to know whether a blowpipe can be designed which will show normal regulation for any ratio which may be selected at random.

Although experiments upon effect of flame regulation on the strength of welds in the first and second series did show a slight deterioration for improper regulation, the results tend to show that the effect must ordinarily be very slight. With a change in the amount of acetylene of perhaps only 2 or 3%, at most, of the total gas volume, it is difficult to believe that much difference in the chemical composition of the materials in the weld can result, especially when the short time that the flame is in contact with any particular portion of the material is considered.

68. *Gas Consumption.*—As was to be expected, the gas rate increased with the size of the blowpipe. The experimental rates are very nearly those given in the catalog of the manufacturers of the blowpipe, particularly for the acetylene. As the ratio of acetylene to oxygen, from the catalog, differs considerably from that found from analyses, it is impossible for both the oxygen and acetylene rates to check very closely with those in the catalog.

The gas rates for blowpipes No. 7 and 8 with double cone regulation appear low, and should follow the dotted lines in Fig. 22. It was noticed when gas samples for these were taken that no second cone appeared with both oxygen and acetylene cocks full-open. There was, therefore, an insufficient supply of acetylene for normal regulation with normal oxygen pressure. The oxygen pressure was therefore reduced to produce normal regulation. This accounts for the low gas rate. The blowpipe body was intended for use only with heads up to and including No. 7, but the No. 8 head was supplied for this work by request. Evidently the acetylene passages, in the body, are barely large enough for the No. 7 head and totally inadequate for the No. 8. Increasing the acetylene pressure might overcome this difficulty. In all the gas consumption curves, therefore, the portion for blowpipes 7 and 8 should be considered abnormal, due to a varying oxygen pressure. The regulation curves show, however, how persistent is the flame's characteristic appearance for these abnormal conditions.

69. *Oxygen Consumption.*—Due to the low pressure of the acetylene, about 0.4 lb. per sq. in. (12 in. of water) and the high oxygen pressure (12 lb. per sq. in. for blowpipe No. 5), it appears probable that the oxygen rate remained constant, or nearly so, for all flame regulations. If any change occurred, it would be a decrease in the oxygen rate as the acetylene rate increased. Omitting abnormal samples, the averages of the oxygen rates for blowpipe 5 are as follows: Both cocks full-open, 7.83; double-cone regulation, 7.48; normal regulation, 7.69; short-cone regulation, 7.53; average, 7.63 cu. ft. per hr. The variations from this average are just the opposite from those expected. The variations range from 2.6% above to 2.0% below the average, and might be caused by an error of one second in the time reading. This leads to the conclusion that the oxygen rate is practically constant for any given blowpipe and oxygen pressure, and is independent of the acetylene rate. This would have been more apparent in the graphs if the oxygen rate had been plotted below the acetylene rate.

The strikingly high gas rate for blowpipe No. 8, for short cone regulation, shown in Fig. 22, is explained by the high oxygen pressure used. If it is assumed that the rate is proportional to the square root of the pressure, the curve for short-cone regulation acetylene and oxygen in Fig. 22 may be corrected approximately as shown by the dotted line.

The increase of oxygen rate with increase of pressure is very noticeable in Fig. 23, and there is a nearly proportional increase in the acetylene rate. Although this increase is not exactly proportional to the square root of the pressures, the difference appears to be less than the experimental error.

70. *Cost of Operation.*—The great increase in the cost of operation as the size of blowpipe increases may be seen from Fig. 24, as well as the small proportion of the cost represented by labor even at the high rate of pay assumed. This indicates that oxyacetylene blowpipes are best adapted, commercially, to plates up to about $\frac{1}{4}$ in. in thickness.

The fact that the welding rate, based on the cross sectional area of weld, is very nearly constant at 17.5 sq. in. per hr. is seen in Fig. 25. This is the value used in estimating the probable welding rate on any given thickness of plate.

The cost of welding plates of any given thickness may be estimated also at 25 cents per cubic inch of filler used. This is, of course, subject to the assumed costs and would be proportionally altered for other values. This cost holds, however, only for plates over $\frac{1}{8}$ in. in thickness and must be doubled for $\frac{3}{64}$ in. plates. It should also be noticed that, provided this rate holds for any type of grooved joint, if the plates were grooved from both sides, as shown at (c), Fig. 8, the cost per foot of weld would be only half that for plates grooved from one side only, as shown at (b), because the required amount of filler would be reduced one-half.

71. *Summary for Tests of Gases.*—The appearance of the blowpipe flame is a very sensitive indicator of changes in the proportions of oxygen and acetylene when near normal regulation.

The average proportion of acetylene at normal regulation is 42.0%, a ratio of 1.38 volumes of oxygen to 1 of acetylene.

The oxygen consumption is practically constant for any given size of blowpipe and oxygen pressure and independent of the acetylene rate.

Apparently the oxygen rate is proportional to the square root of the oxygen pressure.

The percentage of acetylene is very nearly constant for normal regulation with any oxygen pressure.

The minimum oxygen pressure is reached when the flame "back fires" so frequently that satisfactory work is impossible.

The maximum oxygen pressure is reached when the flame "blows out" or is extinguished by the high velocity of the gases.

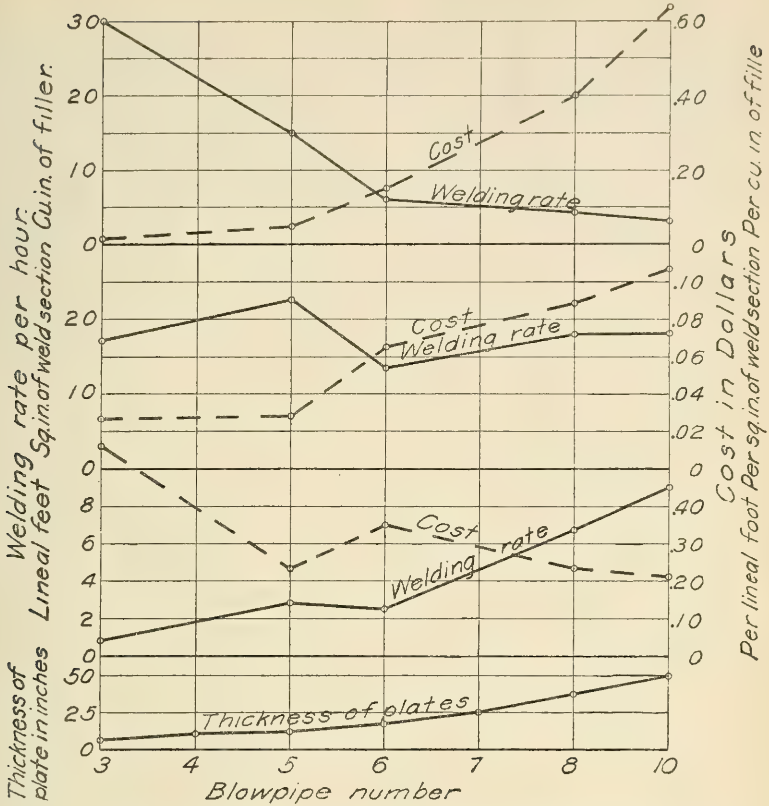


Fig. 25. Welding Rate and Cost in Terms of Length of Weld, Section of Plate, and Volume of Filler for Blowpipes of Various Sizes.

Normal regulation is impossible at the maximum oxygen pressure and is obtained only at some lower pressure.

The cost of operation for oxyacetylene blowpipes rises very rapidly as the thickness of plate is increased, reaching, possibly, four dollars an hour for the gas and labor for work on plates of three-quarter inch thickness.

The welding rate is nearly constant at 17.5 sq. in. of weld section per hour.

The cost of welding beveled plates is about 25 cents per cubic inch of filler, assuming oxygen at three cents per cubic foot, and acetylene at one cent per cubic foot, and labor at 30 cents per hour.

V. General Conclusions.

72. *Heat Treatment.*—The meager amount of information obtained regarding the effect of heat treatment and subsequent working of the welded material leaves an important and probably very fertile field still to be covered. The rather remarkable results obtained by forging after welding appear to be in agreement with the known properties of metals. Highly heated steel, upon cooling, has a coarse crystalline fracture and low tensile strength. This condition can be improved by reheating to the lowest temperature which will produce a fine grain and then cooling. In this way, the finest grain and also the highest tensile strength will be obtained. Steel heated to, or near, fusion is "burnt" and greatly damaged. The injurious effects of "burning" of steel appear to be due, in part at least, to the "oxidation of the faces of the crystalline grains which compose the metal, by inward diffusion of the atmospheric oxygen" (Howe). The oxyacetylene blowpipe flame, if properly regulated, is a reducing flame as is shown by the reduction of the surface film of oxide of the filler wire, and the injurious oxidizing effect may be small in metal welded by an oxyacetylene flame. "Burnt" metal can never be completely restored to its original condition. While annealing alone will restore steel if merely overheated, steel which is "burnt" requires mechanical working, such as hammering or rolling while hot to cause much improvement. For a discussion of the cause of and remedies for "burnt" steel see Howe's "Iron, Steel and Other Alloys," pp. 241—276.

It seems probable that the coarse crystalline fractures and low efficiencies found for these oxyacetylene welds are produced necessarily by the very nature of this or any other welding process which requires fusion of the material. It is even possible, then, that blowpipe welding may prove superior to other methods involving the use of gas or coal, since the reducing action of the oxyacetylene flame may prevent the oxidizing of the crystals found in "burnt" steel. In any case, maximum efficiencies can be obtained only by using every available means to reduce the effects of overheating. This would require annealing and, if practicable, hammering or rolling.

It is often claimed that welds can be strengthened any required amount by adding filler to increase the thickness. This, however, is obviously only a partial remedy, as the material adjacent to that where filler is added is always overheated. When rupture occurs just outside the weld, due to this overheating, the weld can not be considered to be as strong as the rest of the material.

73. *Efficiency.*—Skill in the manipulation of the oxyacetylene blowpipe and in making welds may readily be acquired by the ordinary workman. As already stated, the appearance of the flame is a delicate indication of proper regulation. The principal precaution to be observed by the workman is to be sure that thorough fusion has taken place.

The data on consumption of gases, and on pressure and regulation given in IV. Tests of Gases and Flame Regulation may be applied to various conditions of operation. The cost of operation of a blowpipe rises very rapidly as the thickness of the plate to be welded increases, and this fact may limit the field of usefulness of the oxyacetylene blowpipe to the welding of thin plates and parts and to emergency repair jobs.

The efficiencies of welds obtained in the investigation are summarized rather fully in paragraphs 31 to 36, 53 to 58, and 67 to 71. A consideration of the results leads to the conclusion that thorough fusing of the material in the weld and forging of the finished weld were the only conditions which resulted in any noticeable increase in the efficiency of the welds. Forging after welding produced a decided increase in the strength of the welds and also in the ductility of the fused metal—apparently the increase in efficiency of the weld was about 10%. In the three strips in which thorough fusion took place throughout the weld, the average efficiency was the highest obtained in the tests. In view of the comparisons hitherto made, the efficiency found for one of these strips, 86.6 %, may be expected to be fairly representative of welds in $\frac{1}{8}$-in. steel when fusion has occurred throughout the weld.

The average technical article describing this process apparently lays too much emphasis upon the necessity for very careful flame regulation and for pure oxygen and acetylene, as well as on the value of preheating and hammering the weld as it is made, in securing high efficiency. A claim of 100% efficiency is insupportable. It appears that 85% is about as high as may be expected in practice if the weld is of the same thickness as the plate.

In spite of certain inherent defects the oxyacetylene process is well adapted to many welding operations, and it is likely to grow in favor as its advantages are understood.

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THE SPONTANEOUS COMBUSTION OF COAL

WITH SPECIAL REFERENCE TO BITUMINOUS COALS OF THE ILLINOIS TYPE

BY

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AND

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ENGINEERING EXPERIMENT STATION

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THE SPONTANEOUS COMBUSTION OF COAL

WITH SPECIAL REFERENCE TO BITUMINOUS COALS OF THE ILLINOIS TYPE

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THE SPONTANEOUS COMBUSTION OF COAL

WITH SPECIAL REFERENCE TO BITUMINOUS COALS OF THE ILLINOIS TYPE

I. Introduction

The coal production in Illinois, in 1907 and also in 1908, amounted, each year, to 51 million tons, valued at 52 million dollars. There was a slight increase in 1908 over the tremendous production in 1907, in spite of the labor troubles which caused a complete shut-down of mining, beginning with the April, 1908, conference of miners and operators. The general business depression of that year caused many consumers to use the cheaper grades of bituminous coals in preference to the more expensive anthracite, and, since production at the mines was thus stimulated before and after the shut-down, the public felt no shortage of fuel. Such a situation is unnecessarily expensive both for the consumer and the miner, as a uniform daily output is necessary in order to procure and maintain the most economical production of coal. However, having secured such a uniform daily output, it is manifest that a production of coal so great as that given above cannot be guaranteed to meet fluctuations in daily demand.

To guard against unknown and unforeseen conditions, such as labor difficulties, variations in output or delay in transportation, the large manufacturing interests are beginning to see the need of storing large amounts of reserve fuel. Variations, due to seasonable demands of fuel for domestic purposes, also necessitate the storage of coal either by the mining interests or by the coal dealers. In the maritime world, the storage of coal is one of the great problems of today. Our large battle ships and ocean greyhounds use upwards of 500 tons of coal per day, and hence coal must not only be stored on shipboard, but large reserve supplies must be on hand at the various coaling stations.

On the other hand, wherever large quantities of bituminous coal are stored,—and bituminous coal furnishes by far the greatest part of the energy used at the present day,—the danger arising from spontaneous combustion must be taken into consideration, and hence elaborate and costly measures are being taken to avert this hidden peril. The problem of spontaneous combustion is rapidly being recognized as the great problem in the storage of bituminous coals.

The United States government, which uses upwards of a quarter of a million tons of coal yearly for the navy alone, has taken great precautions to avert the danger of spontaneous combustion in its new coal pile at Bradford, on Narragansett Bay, near Newport, where the storage capacity is about 60 000 tons.

The coal bins or pockets are provided with temperature tubes, so that if incipient heating should occur it will be discovered and located long before a temperature has been reached at which combustion commences. These tubes consist of lengths of 4 in. galvanized pipe about 20 feet long, set in the bin floors and projecting upwards through the coal pile. They contain thermostats which are arranged to indicate temperatures in excess of 150°F. Circuits are run from the 232 tubes to a general annunciator in the superintendent's office, so that if heating does occur an alarm is at once sounded and the exact position of the pile where the heating has developed is shown on the indicator.

The temperature of 150°F. was decided upon as the danger point as the result of numerous experiments made by the Navy Department which indicated that if the temperature of the coal reached this point the increase in temperature beyond was very rapid.[1] At the New York Navy Yard, compartments of 525 gross tons capacity have been built. The floors of these bins are of portland cement, and the side walls are made of a mixture of portland cement, sand, and anthracite boiler cinders. The roofs are of iron[2].

The danger of spontaneous combustion on shipboard is even greater than during ordinary storage, for the coal is usually stored in whatever space is unoccupied by other materials, usually at the side of the vessel between the boiler rooms and the side planking. Here the coal is subjected to the heat of the boiler and engine rooms, and is especially liable to ignite spontaneously.

Up to the present time a great deal of excellent work together with a considerable amount of theorizing regarding the nature and cause of spontaneous combustion has been done, but the views presented have been very contradictory, as a study of the Appendix will reveal. It seemed probable, therefore, that the differences in the particular varieties of coal worked with might have been the cause of the various theories advanced, and that seeming truths and generalizations drawn from work on a specific coal are not applicable to coals in general.

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[1] Chemical Engineering, June 1906

[2] Engineering News, July 21, 1904, page 68

On assembling the results of many investigations in this field, it was found that the primary conditions which lead to spontaneous combustion are considered to be as follows:

(1) The presence of pyrite.
(2) The size of coal.
(3) The initial or induced temperature of the coal.
(4) The presence of moisture.

While these results are extremely suggestive, they cannot be looked upon as conclusive or necessarily applicable to the problems in this region connected with coal storage. Two reasons, at least, may be given in support of this statement. (1) Such an assembling of results gives no suggestion as to the relative importance of the various influences. (2) The conclusions of an investigator based upon experiments with one type of coal might not apply in the case of a coal differing in texture and chemical composition. These two features must be understood for any given type of coal before any safe statements can be made regarding that particular region. For example, while it may be true of any coal that the above enumerated causes are operative, it is more important in any case to know the order of their importance. Again, in the case of coals from the midcontinental fields, i. e., of the Illinois type, a peculiarity of the composition exists which may enter into the problem as a factor. The coals of this region, for example, are characterized by a high content of moisture seldom below 10 per cent and averaging 12 to 15 per cent at the vein. This is in marked contrast to coals of the same general type of the eastern United States and Europe, where this factor rarely exceeds 2 to 4 per cent. Again, this fact, while perhaps not so significant in itself is always accompanied by another item which may have some bearing in that this large water content is always accompanied by a higher content of oxygen combined as a part of the organic matter, in contrast with the lower oxygen content of the low moisture bituminous coals. Also, the high sulphur content of Illinois coal, ranging from 1 to 6 per cent, with the average at about 4 per cent, may materially influence the spontaneous combustion of this type of coal.

The Illinois bituminous coals, with their high moisture and ash, varying amounts of sulphur and inert volatile matter, seem, therefore, to require special study in order to establish the reasons for their property of spontaneous combustion. The subject naturally divides itself into three subdivisions: first, the determination, if possible, of the causes of spontaneous combustion; second, the relative importance of these causes; and third, the removal, if possible, of this property of spontaneous combustion either through the treatment of the coal by chemical processes or through certain methods of handling.

II. OUTLINE OF EXPERIMENTAL INVESTIGATIONS

GENERAL DESCRIPTION OF METHODS AND APPARATUS

Coal from Williamson county, Illinois, marketed under the trade name of "New Ohio," was used for these experiments. The composition of the various samples will be found on pages 9 and 14. About one-half ton of large lumps was required for the experiments. These lumps were ground to the requisite sizes. The grinding was done in a small Chipmunk crusher and the ground coal was then run through a revolving screen, by which it was sized. The screen used was of the revolving or trommel type, made of perforated steel plate about 6 ft. long and 1 ft. in diameter, in which holes of the following sizes were drilled: $\frac{1}{8}$ inch, $\frac{1}{4}$ inch, $\frac{3}{8}$ inch, $\frac{1}{2}$ inch, $\frac{3}{4}$ inch, 1 inch. The coal coming through the-$\frac{1}{4}$ inch holes, known as size $\frac{1}{8}$-$\frac{1}{4}$ was always screened twice because a small amount of dust escaped the $\frac{1}{8}$-inch holes the first time; in order to make the $\frac{1}{8}$–$\frac{1}{4}$ size dust-free it was re-screened. Each time only enough coal was ground and screened to meet immediate demands and any left over was thrown away, so that the coal used was always fresh and unoxidized.

The most potent elements in the case were believed to be temperature, fineness of division, pyrites and the amount of moisture present. These are taken up in the order given.

1. *Effect of Temperature and Size.*—In studying the effect of external temperature the general principle was adopted of placing rather large, 25 to 35 lb., samples within an insulated space,

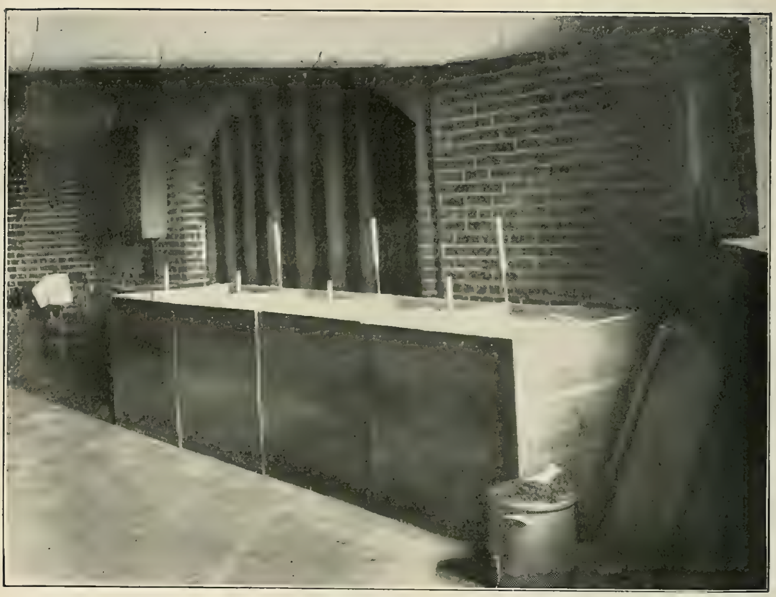

FIG. 1.
GENERAL VIEW OF THE OVENS, SHOWING THERMOMETER ARRANGEMENT AND A SAMPLE JAR OF COAL.

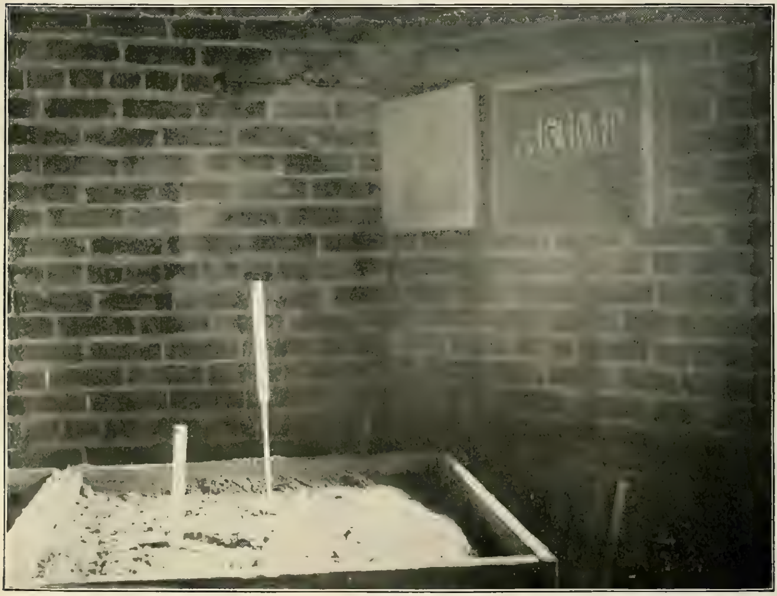

FIG. 2.
A VIEW OF THE TEMPERATURE REGULATING APPARATUS AND DETAIL OF ONE OF THE OVENS.

where the atmosphere immediately surrounding the sample could be kept under exact control. By means, then, of thermometric readings taken within the coal mass and also from the atmosphere of the chamber, any oxidation within the coal sample would be indicated by a rise of temperature above that of the surrounding atmosphere. The details as to the time, temperature, construction and general procedure were as follows:

2. *Methods and Apparatus.*—The coals were placed in the constant temperature ovens for a period of three days each, as, in the preliminary experiments that were run, it was found that a period of 72 hours was sufficient to give the maximum rise in temperature. The following temperatures were maintained in four different ovens; 40°, 60°, 80°, 115° Centigrade. The coal was first placed in the 40° oven, and after a period of three days, it was moved to the 60° oven; after another period of three days, it was moved to the 80° oven; and finally, after another period of three days, it was moved to the 115° oven; after remaining in this oven for three days the coal was removed. A 5-gal. stone jar having the bottom perforated with ½-in. holes was used as a container for the coal. A jar of this size held a sample of coal weighing about 35 or 40 lb.

The ovens were constructed as follows. They consisted of two wooden boxes, one set inside the other. The boxes were in the form of cubes, the outer box being a 3-ft. cube made of 1⅛-in. pine boards; the inner box was also in the form of a cube, made of the same material only it was 8 in. smaller than the outside box. This left a space of 4-in. on all sides between the two boxes, and this space was tightly packed with mineral wool, the inner box being well insulated in this manner. Across one corner of the inner box a board was nailed. This board was 4 in. shorter than the box and was nailed into the box so as to leave a clear space of 2 in. at the top and bottom of the box. The triangular space formed by this board and the corner of the box was lined with ¼-in. asbestos board so as to insulate it. This space then formed a chimney, and near the bottom of this chimney the electric lights used to heat the boxes were hung. The temperature was regulated by means of a mercury regulator which consisted of a large bulb of mercury expanding up a capillary tube. A platinum wire was fused into the bulb so as to be in contact with the mercury. Down the top of the capillary tube a long, fine needle was placed so that when the mercury was expanded to a certain height at a definite temperature the mercury would just come in contact with the needle. Wires were run from the regulator to a telegraph relay, the mercury regulator being connected in series in this circuit. This outfit was run by storage battery current. The telegraph relay was used to make and break the 220-volt circuit on which the lights used for heating were connected.

The jars of coal were placed on several bricks in the inner box, the bricks being arranged so as to elevate the jar high enough so that it would be in the middle of the box, and also to allow the air around the jar to circulate freely. The cover of the inner box was then put into place, and through the holes in the latter several long thermometers (about 2½ ft. long) were placed to indicate the temperature of the air in the box and also the temperature of the coal. The thermometers used to indicate the temperature of the air in the box were placed so that one was near the heating chimney and the other was at a point farthest from it. The thermometer used to indicate the temperature of the coal was placed so that the bulb was 4 or 5 in. below the surface of the coal. Readings of these temperatures in degrees Centigrade were taken every morning and afternoon.

In the first run, called Series 1, five sizes of the coal were used. These samples were not what would be known as air-dry, because the coal was used as soon as it was ground; the large lumps, however, were air-dry. The five sizes were as follows:

Size 0: This size included some of the coal that went through the smallest holes in the screen and then was ground in a disk pulverizer until it was very finely divided. About 75 per cent of this size went through a 120-mesh screen, and all of it went through an 80-mesh.

Size 0–⅛: This coal went through the ⅛ in. holes in the large revolving screen.

Size ⅛–¼: This coal went through the ¼ in. holes in the screen.

Size ¼–⅜: This coal went through the ⅜ in. holes in the screen.

Size ⅜–¾: This size was a mixture of equal parts of the coal that went through the ½ in. and the ¾ in. holes in the revolving screen; it was thought that there would not be enough difference between the results of the ½ in. and the ¾ in. size, so the two were mixed in equal proportions.

DETAILS OF EXPERIMENTS

Experiments were conducted in 15 series. Each series represented experiments upon certain chosen sizes of coal, and all the coals of a given series were subjected to the same conditions. Each series differed from the others by one variable as to condition, such as dry or wet, varying content of pyrites, etc.

Composition of Coal. The composition of the coal used in the first five series, as indicated by a proximate analysis, was as follows:

TABLE 1

	Size 0–$\frac{1}{8}$ per cent	Size $\frac{1}{8}$–$\frac{1}{4}$ per cent
Moisture	4.16	4.62
Volatile Matter	33.48	33.37
Fixed Carbon	50.86	50.88
Ash	11.50	11.13
Total	100.00	100.00
Sulphur	1.26	1.29
Calculated to Dry Coal		
Volatile Matter	34.92	34.78
Fixed Carbon	53.08	53.58
Ash	12.00	11.64
Total	100.00	100.00
Sulphur	1.32	1.35

The pyritic iron was determined by taking the difference between the total iron in the coal and the iron soluble in dilute hydrochloric acid. The results for the above two samples are as follows:

	Size 0–$\frac{1}{8}$ per cent	Size $\frac{1}{8}$–$\frac{1}{4}$ per cent
Total iron	1.91	1.73
HCl soluble Fe	0.73	0.67
Pyritic iron	1.18	1.06
Calculated Pyrite content	1.76	1.60

Inasmuch as more of the larger sizes were used than the finer, the average pyrite content of the coal was taken as 1.65 per cent.

Series 1.—A jar of each of the four largest sizes of coal was placed in the ovens in the same increasing ratio of size of the coal and the temperature of the oven, e. g., size 0-$\frac{1}{8}$ was put in the 40° oven, size $\frac{1}{8}$–$\frac{1}{4}$ in the 60° oven, size $\frac{1}{4}$-$\frac{3}{8}$ in the 80° oven, and size $\frac{3}{8}$–$\frac{3}{4}$ in the 115° oven. This method of procedure was adopted to save time, for by this means all the ovens could be filled at once, and since it took 12 days for a coal to pass through the four ovens, a considerable saving of time resulted, and the large sizes of coal were not oxidized to an appreciable extent at these low temperatures. After the coals had remained in the ovens for three days, they were moved up to the next oven, size $\frac{3}{8}$–$\frac{3}{4}$ was taken out of the 115° oven and the next smaller size put in, and size 0 was put in the 40° oven. The reading of the temperatures was made in the morning and afternoon, chiefly to see that the regulators were working well and that the lights were not burned out, and also to get the increase in temperature of the coal over that of the ovens. As is shown in Table 2, the

TABLE 2

SERIES 1—DRY COAL—1.65 PER CENT PYRITE

	Coal 0	Coal 0–$\frac{1}{8}$	Coal $\frac{1}{8}$–$\frac{1}{4}$	Coal $\frac{1}{4}$–$\frac{3}{8}$	Coal $\frac{3}{8}$–$\frac{3}{4}$
Time in hours	96.0	89.0			
Oven temperature °C	38.8	40.0			
Coal temperature °C	41.7	42.5			
Rise temperature °C	2.9	2.5			
Time in hours	89.0	76.0	89.0		
Oven temperature °C	60.0	60.5	60.0		
Coal temperature °C	65.0	63.7	63.5		
Rise temperature °C	5.0	3.2	3.5		
Time in hours	77.0	74.0	76.0	89.0	
Oven temperature °C	80.0	80.0	79.8	77.0	
Coal temperature °C	95.0	91.1	89.7	78.0	
Rise temperature °C	15.0	11.1	9.9	1.0	
Time in hours	42.0				
Oven temperature °C	108.0				
Coal temperature °C	168.0				
Rise temperature °C	60.0				
Time in hours	72.0	89.0	74.0	76.0	89.0
Oven temperature °C	108.0	109.0	107.8	108.0	107.0
Coal temperature °C	154.0	140.0	133.2	127.9	122.4
Rise temperature °C	46.0	31.0	25.4	19.9	15.4

maximum rise in temperature in some cases took place before the end of three days. This was especially the case in the dry, finer sizes. The average temperature of the ovens and the temperature of the coal at the end of the three days are shown in Table 2.

Series 2. Series 2 was the same as Series 1, the only difference being that the coal in Series 2 was thoroughly wet before being placed in the ovens.

Before beginning Series 2, in order to get some idea as to the oxidation of the coal and the amount of oxygen used up by it, the air in the different ovens was analyzed, after the coal had been in the ovens for three days. The results were as follows:

	Oven 1—40°	Oven 2—60°	Oven 3—80°	Oven 4–115°
Per cent CO_2	0.40	1.20	1.00	1.81
Per cent Oxygen..........	20.00	18.40	19.40	16.00

Since the oxygen content decreased so much, it was thought

TABLE 3

Series 2—Wet Coal—1.65 Per Cent Pyrite

	Coal 0	Coal 0–$\frac{1}{8}$	Coal $\frac{1}{8}$–$\frac{1}{4}$	Coal $\frac{1}{4}$–$\frac{3}{8}$	Coal $\frac{3}{8}$–$\frac{3}{4}$
Time in hours....................	72.0	81.0			
Oven temperature °C	38.5	38.5			
Coal temperature °C	38.3	38.5			
Rise temperature °C	....	....			
Time in hours....................	84.0	72.0	81.0		
Oven temperature °C............	60.0	59.0	59.5		
Coal temperature °C	57.5	58.5	62.4		
Rise temperature °C	....	....	2.9		
Time in hours....................	72.0	84.0	72.0	81.0	
Oven temperature °C	80.0	80.0	80.0	80.0	
Coal temperature °C	86.5	85.5	86.3	85.6	
Rise temperature °C	6.5	5.5	6.3	5.6	
Time in hours	48.0				
Oven temperature °C	111.5				
Coal temperature °C	168.3				
Rise temperature °C	56.8				
Time in hours	72.0	72.0	84.0	72.0	81.0
Oven temperature °C	114.0	111.9	110.2	112.5	111.5
Coal temperature °C	164.8	148.2	131.0	128.0	125.5
Rise temperature °C	50.8	36.3	20.8	16.5	14.0

necessary to ventilate the ovens so as to maintain atmospheric conditions. This was done by boring several ½-in. holes through the walls of both boxes near the bottom and putting a ½-in. glass tube through the two walls. One of the tubes was placed so that the fresh cool air that came in was delivered at the bottom of the heating chimney, and the other tube delivered its air at the opposite side of the box. At the top of the box a take-off pipe of the same size was inserted.

Series 3.—In Series 3 and 4 the content of iron pyrites was increased over the amount in Series 1 and 2 so that the total of iron pyrites in the form of FeS_2 was 3 per cent. This was accomplished by taking some large lumps of pyrite just as it occurs in the coal measures of Vermilion County. This was ground to pass through a 20-mesh sieve, and upon analysis was found to be 87.62 per cent pure. This calculation of purity was based upon the sulphur content of the material, which was 46.73 per cent. In Series 3 the variable from Series 1 is in the content of pyrite which has been increased from 1.65 per cent to 3 per cent. Tests upon the two larger sizes were omitted for the reason indicated in Tables 2 and 3. The oxidation on these larger sizes was too small and not different in character from the reaction upon the finer sizes, hence they were omitted from the subsequent experiments.

TABLE 4

SERIES 3—DRY COAL—3 PER CENT PYRITE

	Coal 0	Coal 0–⅛	Coal ⅛–¼
Time in hours	71.0	71.0	
Oven temperature °C	37.0	39.5	
Coal temperature °C	42.0	42.0	
Rise temperature °C	5.0	2.5	
Time in hours	72.0	71.0	71.0
Oven temperature °C	60.0	60.0	66.0
Coal temperature °C	68.2	67.5	60.0
Rise temperature °C	8.2	7.5	6.0
Time in hours	72.0*	72.0	71.0
Oven temperature °C	75.0	80.0	81.5
Coal temperature °C	88.6	93.5	93.8
Rise temperature °C	13.6	13.5	12.3
Time in hours	30.0		
Oven temperature °C	115.0		
Coal temperature °C	190.3		
Rise temperature °C	75.3		
Time in hours	72.0	72.0*	72.0
Oven temperature °C	115.0	114.0	114.0
Coal temperature °C	161.0	165.0	138.0
Rise temperature °C	46.0	51.0	28.0

*The heat current had been turned off at power house. Coals were left two days longer.

TABLE 5

SERIES 4—WET COAL—3 PER CENT PYRITE

	Coal 0	Coal $0-\frac{1}{8}$	Coal $\frac{1}{8}-\frac{1}{4}$
Time in hours	72.0	72.0	72.0
Oven temperature °C	39.5	40.0	39.5
Coal temperature °C	39.5	39.2	42.3
Rise temperature °C	0.0	....	2.8
Time in hours	72.0	72.0	72.0
Oven temperature °C	60.0	60.0	61.0
Coal temperature °C	56.5	55.7	66.5
Rise temperature °C	....	....	5.5
Time in hours	72.0	72.0	72.0
Oven temperature °C	80.0	80.0	80.0
Coal temperature °C	86.7	82.8	89.8
Rise temperature °C	6.7	2.8	9.8
Time in hours	72.0	72.0	72.0
Oven temperature °C	112.5	115.0	115.0
Coal temperature °C	226.2	172.0	126.0
Rise temperature °C	113.7*	57.0*	11.0

*Upon removal from the oven and standing at room temperature, the interior of the mass within the jar took fire and after a period of from 2 to 3 weeks was consumed.

TABLE 6

SERIES 5—DRY COAL—5 PER CENT PYRITE

	Coal 0	Coal $0-\frac{1}{8}$	Coal $\frac{1}{8}-\frac{1}{4}$
Time in hours	72.0	72.0	72.0
Oven temperature °C	34.0	39.0	40.0
Coal temperature °C	38.0	42.4	42.0
Rise temperature °C	4.0	3.4	2.0
Time in hours	72.0	72.0	72.0
Oven temperature °C	60.5	60.3	61.0
Coal temperature °C	70.0	66.2	66.6
Rise temperature °C	9.5	5.9	5.6
Time in hours	*....	72.0	72.0
Oven temperature °C	....	80.5	81.0
Coal temperature °C	....	88.2	89.2
Rise temperature °C	....	7.7	8.2
Time in hours	72.0	72.0	72.0
Oven temperature °C	122.0	120.0	116.0
Coal temperature °C	185.0	174.0	143.2
Rise temperature °C	63.0	54.0	27.2

*Battery worn out, so regulator did not work; was recharged and put in order.

Series 4.—In Series 4 the conditions of the experiment were precisely as in Series 3, with the exception that the coal was thoroughly wet before placing in the ovens.

Series 5.—In Series 5 the conditions were the same as in Series 1 and 3, with the exception that the content of iron pyrites was increased to 5 per cent.

The first lot of coal being exhausted, a new lot was procured. This was from the same source and was hand-picked as before, but it was deemed advisable to make a careful analysis again. This analysis is shown in the following table.

TABLE 7

	Per cent
Moisture	4.34
Volatile matter	33.38
Fixed carbon	50.25
Ash	12.03
Total	100.00
Sulphur	1.17

Calculated to Dry Coal

Volatile matter	34.89
Fixed carbon	52.43
Ash	12.68
Total	100.00
Sulphur	1.22

The pyritic content of the coal was determined as before. The total iron in the coal was determined, and from it the iron soluble in dilute hydrochloric acid was subtracted; this gave the pyritic iron, and from the latter the pyrite was calculated.

	Per cent
Total iron	1.440
HCl soluble Fe	0.510
Pyritic iron	0.930
Calculated	
Pyrite content	1.397

The iron was determined volumetrically by the Zimmermann-Reinhardt method, as modified by Jones and Jeffery[1].

It will be noted that the pyrite content of the second lot of coal is slightly less than that used in the former series. This fact was taken into account, however, in making up the pyrite content of the coal; the pyrite used was some of the same lot that was used in making up the first 5 series.

Series 6.—In Series 6 the conditions were the same as those maintained in Series 2 and 4, with the exception that the content of iron pyrites was increased to 5 per cent. The mass was thoroughly wet down before the samples were placed in the ovens.

TABLE 8

SERIES 6—WET COAL—5 PER CENT PYRITE

	Coal 0	Coal 0–⅛	Coal ⅛–¼
Time in hours	72.0	72.0	
Oven temperature °C	40.0	40.0	
Coal temperature °C	41.0	41.0	
Rise temperature °C	1.0	1.0	
Time in hours	72.0	72.0	72.0
Oven temperature °C	62.0	62.0	90.0[2]
Coal temperature °C	62.0	64.5	105.0
Rise temperature °C	0.0	2.5	15.0
Time in hours	72.0	72.0	72.0
Oven temperature °C	83.0	83.0	83.0
Coal temperature °C	90.0	94.0	91.0
Rise temperature °C	7.0	11.0	8.0
Time in hours	72.0	72.0	72.0
Oven temperature °C	110.5	126.0	116.0
Coal temperature °C	210.0[3]	169.0	133.0
Rise temperature °C	100.0	43.0	17.0

Series 7.—In Series 7 the content of iron pyrites was left the same as in the natural coal. It was not thought advisable to carry the amount of iron pyrites above the 5 per cent as used in Series 5 and 6, for the reason that a consistent increase in ac-

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[1] Analyst, Vol. 34, p. 306 (1909).

[2] Battery run down; was recharged; the coal was again thoroughly wet, as it had dried out.

[3] 210° was as high as the thermometer would register. Upon removal from the oven the coal took fire, as in Series 4.

TABLE 9

Series 7—Mixed Coal—Dry and Wet—1.40 Per Cent Pyrite

	Dry	Wet
Time in hours	72.0	72.0
Oven temperature °C	40.0	40.0
Coal temperature °C	44.0	41.0
Rise temperature °C	4.0	1.0
Time in hours	72.0	72.0
Oven temperature °C	62.0	62.0
Coal temperature °C	67.5	62.0
Rise temperature °C	5.5	0.0
Time in hours	72.0	72.0
Oven temperature °C	86.0	83.0
Coal temperature °C	101.5	89.0
Rise temperature °C	15.5	6.0
Time in hours	72.0	72.0
Oven temperature °C	110.5	110.5
Coal temperature °C	128.5	127.5
Rise temperature °C	18.0	17.0

TABLE 10

Series 8—Mixed Coal—Dry and Wet—3 Per Cent Pyrite

	Dry	Wet
Time in hours	72.0	72.0
Oven temperature °C	40.0	41.0
Coal temperature °C	45.5	44.0
Rise temperature °C	5.5	3.0
Time in hours	72.0	72.0
Oven temperature °C	62.0	62.0
Coal temperature °C	67.0	65.5
Rise temperature °C	5.0	3.5
Time in hours	72.0	72.0
Oven temperature °C	83.0	83.0
Coal temperature °C	95.0	93.0
Rise temperature °C	12.0	10.0
Time in hours	72.0	72.0
Oven temperature °C	148.0	147.0
Coal temperature °C	192.0	198.0
Rise temperature °C	44.0	51.0

tivity accompanies the increase of pyrites to 3 per cent, and again to 5 per cent, which seemed ample verification of the principle involved. Moreover, this latter amount approximates the limit of this substance as actually found in coals of this region. However, the variable employed in this series was the fact that sizing of the coal was not carried out. The lump material was passed through a small Chipmunk jaw crusher, set to deliver the coal in pieces not exceeding ¼ in. to ½ in. in diameter, but carrying with it a very considerable amount of dust and fine particles. Since this plan involved the use of but one sample to cover the mixture of sizes, the dry and wet mixtures were carried along parallel and are covered in the table for Series 7.

Series 8.—In Series 8 the sample of coal was prepared exactly as in Series 7, with the exception that the content of pyrites was increased to 3 per cent. Parallel jars of wet and dry coal were carried through the series as in 7.

Series 9.—In Series 9 the conditions were the same as in Series 7 and 8, with the exception that the content of pyrites was increased to 5 per cent. Parallel samples of wet and dry material were carried through as before.

TABLE 11

SERIES 9—MIXED COAL—DRY AND WET—5 PER CENT PYRITE

	Dry	Wet
Time in hours	72.0	72.0
Oven temperature °C	41.0	40.0
Coal temperature °C	47.0	40.0
Rise temperature °C	6.0	0.0
Time in hours	72.0	72.0
Oven temperature °C	62.0	62.0
Coal temperature °C	68.0	65.0
Rise temperature °C	6.0	3.0
Time in hours	72.0	72.0
Oven temperature °C	83.0	83.0
Coal temperature °C	95.0	93.0
Rise temperature °C	12.0	10.0
Time in hours	72.0	72.0
Oven temperature °C	142.0	132.0
Coal temperature °C	186.0	180.0
Rise temperature °C	44.0	48.0

Series 10.—In the foregoing series, the evidence was conclusive to the effect that with the finer sizes and the presence of iron pyrites of 3 per cent or over, together with moisture, there resulted a rise in temperature which quickly resulted, upon removal to the air, in combustion of the coal. This property was marked in both the 0 size and the 0–$\frac{1}{8}$ in. size and, since the latter was easy to prepare, it was made use of in the subsequent experiments, together with 5 per cent pyrites, for the purpose of testing the effect of various salt solutions as a possible means of checking the rise in temperature.

In Series 10, two strengths of sodium chloride solution were used with results as shown in Table 12.

TABLE 12

SERIES 10—SIZE 0-$\frac{1}{8}$—5 PER CENT PYRITE

	Wet with 3 per cent NaCl Solution	Wet with 10 per cent NaCl Solution
Time in hours	72.0	72.0
Oven temperature °C	43.0	43.0
Coal temperature °C	43.0	43.0
Rise temperature °C	0.0	0.0
Time in hours	72.0	72.0
Oven temperature °C	63.0	63.0
Coal temperature °C	63.0	62.0
Rise temperature °C	0.0	
Time in hours	72.0	72.0
Oven temperature °C	83.0	82.0
Coal temperature °C	89.0	88.0
Rise temperature °C	6.0	6.0
Time in hours	72.0	72.0
Oven temperature °C	112.0	115.0
Coal temperature °C	180.0	190.0
Rise temperature °C	68.0	75.0

Series 11—In Series 11 the same conditions were maintained as in Series 10, with the exception that 3 per cent and 10 per cent solutions, respectively, of calcium chloride were employed.

TABLE 13

SERIES 11—SIZE 0-$\frac{1}{8}$—5 PER CENT PRYITE

	Wet with 3 per cent $CaCl_2$ Solution	Wet with 10 per cent $CaCl_2$ Solution
Time in hours	72.0	72.0
Oven temperature °C	43.0	43.0
Coal temperature °C	42.0	43.0
Rise temperature °C	....	0.0
Time in hours	72.0	72.0
Oven temperature °C	63.0	63.0
Coal temperature °C	63.0	63.0
Rise temperature °C	0.0	0.0
Time in hours	72.0	72.0
Oven temperature °C	82.0	83.0
Coal temperature °C	91.0	85.0
Rise temperature °C	9.0	2.0
Time in hours	72.0	72.0
Oven temperature °C	124.0	122.0
Coal temperature °C	184.0	148.0
Rise temperature °C	60.0	26.0

TABLE 14

SERIES 12—SIZE 0-$\frac{1}{8}$—5 PER CENT PYRITE

	Wet with Saturated Lime Water
Time in hours	72.0
Oven temperature °C	43.0
Coal temperature °C	43.0
Rise temperature °C	0.0
Time in hours	72.0
Oven temperature °C	63.0
Coal temperature °C	63.0
Rise temperature °C	0.0
Time in hours	72.0
Oven temperature °C	83.0
Coal temperature °C	91.0
Rise temperature °C	8.0
Time in hours	72.0
Oven temperature °C	124.0
Coal temperature °C	168.0
Rise temperature °C	44.0

TABLE 15

SERIES 13—SIZE 0–⅛—5 PER CENT PYRITE

	Wet with 3 per cent $NaHCO_3$ Solution	Wet with 10 per cent $NaHCO_3$ Solution
Time in hours	72.0	72.0
Oven temperature °C	43.0	43.0
Coal temperature °C	43.0	43.0
Rise temperature °C	0.0	0.0
Time in hours	72.0	72.0
Oven temperature °C	63.0	63.0
Coal temperature °C	63.0	63.0
Rise temperature °C	0.0	0.0
Time in hours	72.0	72.0
Oven temperature °C	83.0	83.0
Coal temperature °C	93.0	92.0
Rise temperature °C	10.0	9.0
Time in hours	72.0	72.0
Oven temperature °C	126.0	123.0
Coal temperature °C	174.0	161.0
Rise temperature °C	48.0	38.0

TABLE 16

SERIES 14—SIZE 0–⅛—5 PER CENT PYRITE

	Wet with 3 per cent $FeSO_4$ Solution	Wet with 10 per cent $FeSO_4$ Solution
Time in hours	72.0	72.0
Oven temperature °C	43.0	43.0
Coal temperature °C	43.0	43.0
Rise temperature °C	0.0	0.0
Time in hours	72.0	72.0
Oven temperature °C	63.0	63.0
Coal temperature °C	63.0	63.0
Rise temperature °C	0.0	0.0
Time in hours	72.0	72.0
Oven temperature °C	83.0	83.0
Coal temperature °C	93.0	95.0
Rise temperature °C	10.0	12.0
Time in hours	72.0	72.0
Oven temperature °C	132.0	124.0
Coal temperature °C	181.0	186.0
Rise temperature °C	49.0	62.0

Series 12.—In Series 12 the same conditions as to size and pyritic content were maintained, the wetting of the coal being accomplished with a saturated solution of lime water.

Series 13.—The same size of coal with the same pyritic content was employed as in Series 10–13 inclusive, excepting that the solutions used were 3 per cent and 10 per cent respectively, of sodium bicarbonate.

Series 14.—In Series 14 the conditions as to size and pyritic content were maintained as in Series 10–13 inclusive. The solutions employed, however, were 3 per cent and 10 per cent of sulphate of iron.

Series 15.—In Series 15 the principle employed was that of subjecting the sample to pre-heating at temperatures approaching the extremes attained in the ovens under the several series preceding. This series was made up as follows:

One jar of size 0–$\frac{1}{8}$, 5 per cent pyrite, dry.

One jar of mixed coal, i. e., a mixture of about equal parts of sizes, 0–$\frac{1}{8}$, $\frac{1}{8}$–$\frac{1}{4}$, $\frac{1}{4}$–$\frac{3}{8}$, and $\frac{3}{8}$–$\frac{3}{4}$, made up to 5 per cent pyrite, dry.

One jar of exceedingly fine coal, finer than ordinary dust, made by grinding the coal for 100 hours in a ball mill, the latter being a large iron jar with a porcelain lining, having a screw cover. About equal parts of coal and 1 in. to 1$\frac{1}{2}$ in. quartz pebbles were put into the jar. After grinding, the coal was sifted through a 200-mesh sieve so as to remove any small lumps, and was then made up to 5 per cent pyrite, dry.

These three jars of coal were placed in the 40° oven first and moved up after 3 days, as described previously. After being taken from the 115°–120° oven, they were allowed to cool for 3 days and then were replaced in the oven for 3 days, the rise in temperature in all cases being noted.

TABLE 17

SERIES 15
First Heating

	Mixed Coal
Time in hours	72.0
Oven temperature °C	120.0
Coal temperature °C	163.0
Rise temperature °C	43.0

Second Heading

Time in hours	72.0
Oven temperature °C	135.0
Coal temperature °C	146.0
Rise temperature °C	11.0

First Heading

	Size 0–⅛
Time in hours	72.0
Oven temperature °C	140.0
Coal temperature °C	210.0
Rise temperature °C	70.0

Second Heading

Time in hours	72.0
Oven temperature °C	136.0
Coal temperature °C	155.0
Rise temperature °C	19.0

First Heading

	Ball Mill Size
Time in hours	48.0
Oven temperature °C	69.0
Coal temperature °C	205.0
Rise temperature °C	136.0

Second Heading

Time in hours	72.0
Oven temperature °C	64.0
Coal temperature °C	73.0
Rise temperature °C	9.0

Third Heading

Time in hours	72.0
Oven temperature °C	147.0
Coal temperature °C	220.0
Rise temperature °C	73.0

III. Discussion of Results

DISCUSSION AND PRESENTATION OF DATA

Series 1.—In order to make possible a more critical and comparative study of the various series, the temperature increases as tabulated in Series 1 to 15 were plotted in the form of curves, in which the oven temperatures were taken as the abscissas, and the rise over the oven temperatures as the ordinates. These curves shows many interesting results, and a detailed study can be more advantageously made by reference to the curves rather than to the temperature tables.

Fig. 3 shows that the temperature increase is greater as the size of the coal decreases and that most of the oxidation, assuming it may be measured by the rise in temperature, takes place above 60°C., with a more positive index of activity than at 80°. In examining these details of oxidation and the accompanying temperatures, it is very suggestive to review briefly the studies

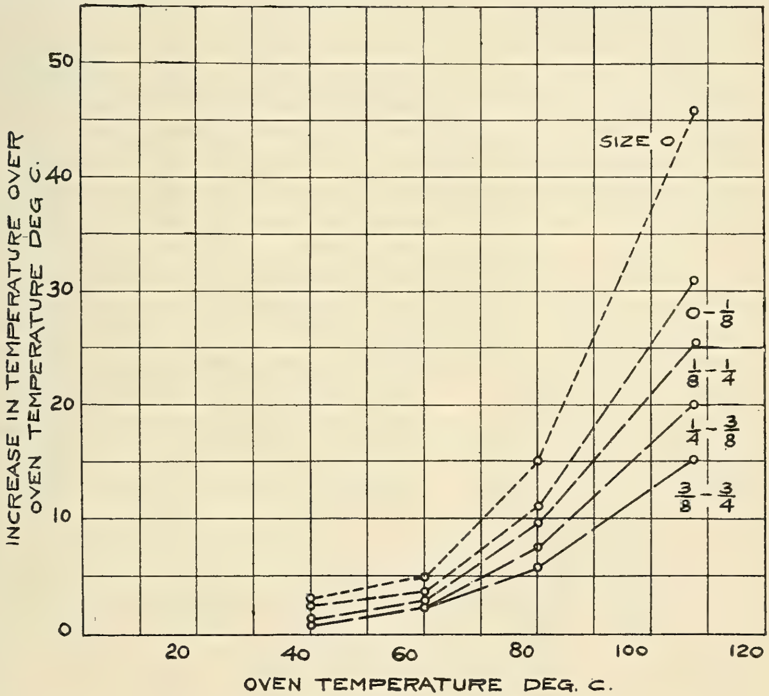

FIG. 3.
SERIES 1—1.65% PYRITE—DRY COAL.

on oxidation temperatures as carried out by Parr and Francis.[1] Those studies were conducted upon 2-gram samples of coal, suspended in an atmosphere of oxygen, with one thermometer for reading the temperature of the coal and another for indicating the temperature of the surrounding gas. In addition to the temperature rise of the coal, the appearance of carbon dioxide in the circulating gas served as an index of the starting and to some extent of the oxidation. In these previous experiments, the observed point where carbon dioxide appeared in the escaping gas was, in general, from 112°C. to 125°C., and the oxidation became so active as to show a marked increase in the internal coal temperature. From this point onward, the conditions for arriving at active combustion were quickly reached. Comparing these facts with those indicated by the curves in Fig. 3 we see a striking suggestion of chemical action other than that which results in the formation of CO_2. For example, at 80° in Fig. 3, all of the samples show a slight increase in temperature over the temperature of the oven atmosphere. It is evident that in these large 40-lb. samples a much more sensitive index of the inception of heat generation is obtained than with the small 2-gram samples of the earlier experiments, so that doubtless chemical action in some form must be considered as having commenced at a temperature considerably lower than the 110° to 120° shown in those experiments. In the present tests, it assumes positive activity quite uniformly at about 80°C.

An element not usually considered may here enter into the case, and that is the initial oxidation of coal which does not show itself in the form of CO_2. Parr and Barker[2] and also Chamberlain[3] have shown that freshly mined coals have a great avidity for oxygen, which enters into combination presumably with the unsaturated hydrocarbon compounds of the coal, and this action goes on at ordinary temperatures. Just what heat increment may be due to this action or what acceleration of the action may result from an increase of temperature has not been investigated. Doubtless, however, this initial oxidation extends over and merges into the more pronounced form, which shows itself both in the presence of CO_2 and in a marked increase in temperature. This may be a partial explanation, at least for the peculiarity of the curve in Fig. 6 of Series 3. A still more noticeable suggestion of the earlier studies on oxidation is found in the higher temperatures. For example, with the oven temperature at 108°, these larger coal masses have attained temperatures ranging from 115° to 145°, and from this latter point, the progress to ignition temperatures as indicated in the earlier tests on the small samples would be very rapid. This was found to be the case, as will be seen from a study of the subsequent experiments.

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[1] Bulletin No. 24, U. of I., Eng. Exp. Sta., June, 1908.

[2] Bulletin No. 32, U. of I., Eng. Exp. Sta., March, 1909.

[3] Bulletin No. 383, U. S. G. S., 1909.

Series 2.—From the curves of Series 2, Fig. 4, it may be seen, as expected, that any heat generated by the process of oxidation is used in driving off the water with which the coal was thoroughly soaked before putting in the ovens. At 80° C., however, we get an increase in temperature over the oven temperature, even though the coal still contains some moisture. It is to be noticed, however, that the final increase in temperature of the two finer sizes is somewhat greater than in Series 1, when the same coal was used dry.

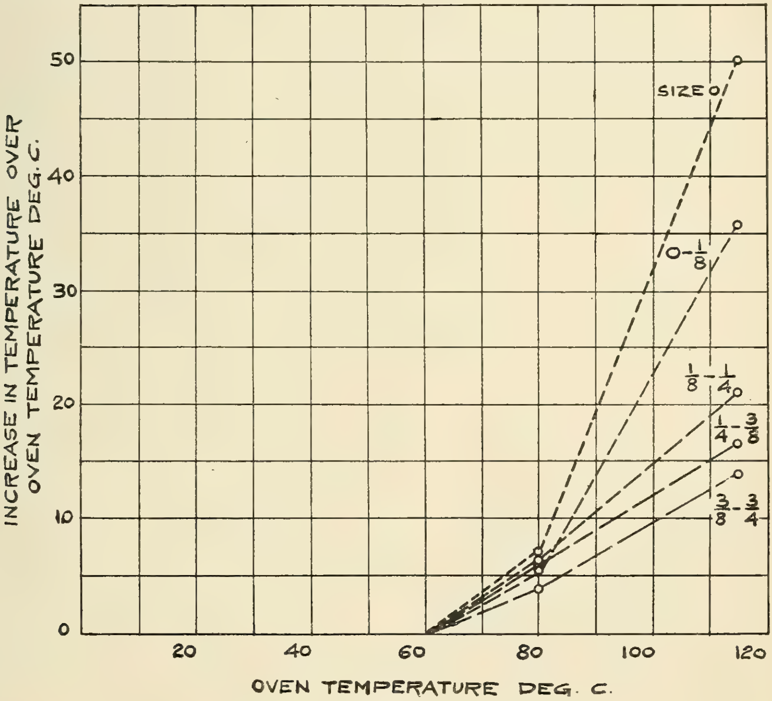

FIG. 4.

SERIES 2—1.65% PYRITE—WET COAL.

Series 3. — Fig. 5, giving the results of Series 3, shows a new and interesting phenomenon, viz., the effect of the size of the coal on the rate of oxidation. Series 1 showed that the fine coals oxidize more than coarse sizes, and also gave an indication of the rate of oxidation, although this was not noticed in time to make a detailed study of it in the first series. In Series 3, however, temperature readings were made every few hours during the time that size 0 was in the 115°–120° oven. As is seen in Fig. 5, the curve of size 0 is made up of two curves, one of which rises to an excess temperature of 75.3° and the other shows an increase of 46°, which is even lower than the temperature increase of the next size, which is 51°. The first temperature of 75.3° was reached after the coal had been in the oven only 30 hours, and from that time until the end of the 72 hours, the temperature gradually decreased to 46°, which was the final temperature. The results of this study of the rate of oxidation, as measured by the increase of the coal temperature over the oven temperature is shown in graphical form in Fig. 6.

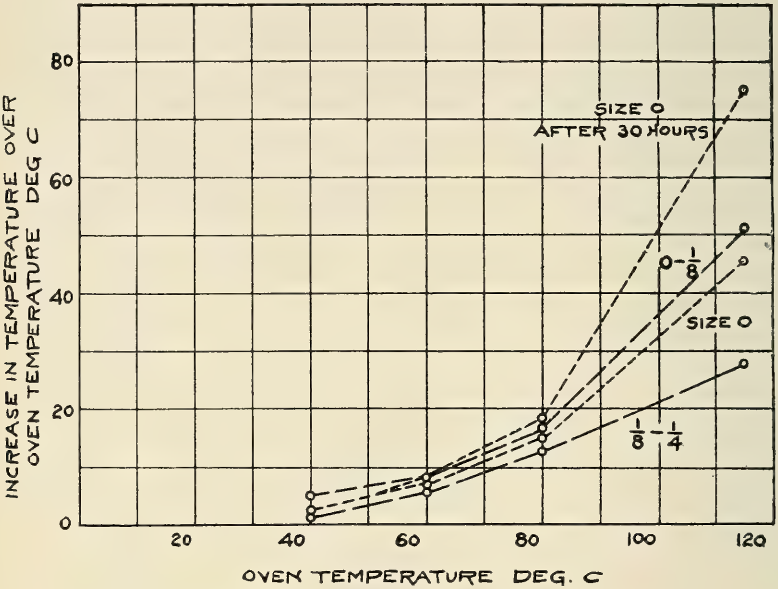

FIG. 5.
SERIES 3—3% PYRITE—DRY COAL.

As seen from this curve the temperature increased very rapidly during the first 30 hours, when it reached a maximum, and it is very probable that at this point this fine size of coal had satuated itself with oxygen. The temperature then gradually decreased until the final temperature was only a little more than one-half the maximum temperature attained. This phenomenon was observed only in the case of the finest size, size 0; the rise in temperature of the coarser sizes was a gradual rise over the entire period of 72 hours. If an average between the maximum and final temperature of size 0 is taken, then a consistent, though not very marked rise in temperature of Series 3 over Series 1, is noticed. These two series are the same throughout, excepting their pyrite content.

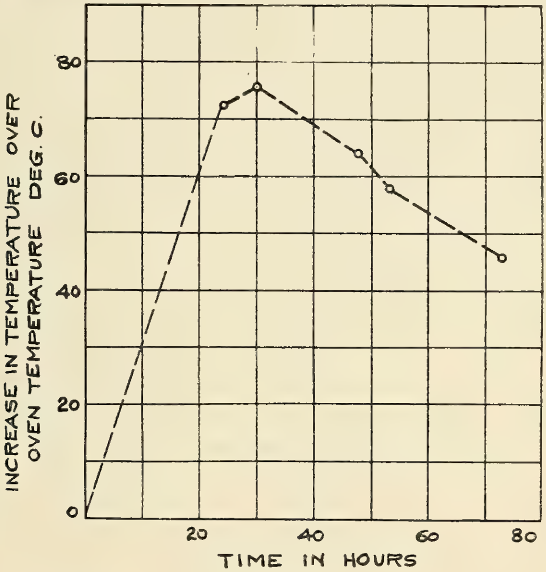

FIG. 6.

SERIES 3—3% PYRITE—SIZE 0—DRY COAL.

Series 4.—Series 4 was coal having the same pyrite content as the preceding series, only in this case the coal was first thoroughly wet. Several new points are seen. Size $\frac{1}{8}$–$\frac{1}{4}$, which was as dust free as it was possible to make it, dried out very soon and showed an increase in temperature even in the 40° and 60° ovens, whereas the two finer sizes did not even get dry at these temperatures. Size 0, at the end of three days, showed an increase over the oven temperature, of 113.7°, this being as high as the thermometers would register. On removal from the oven and on examination the following day, it was found that the coal had taken fire and that the thermometer was not far enough down in the coal to measure the total increase in temperature. The coal took fire in the middle of the jar, and, because of the slight access of air, the burning was only a slow smoldering. The jar was left out in the room temperature for about two weeks after it was taken from the oven, and was then re-examined. It was found that the coal on the interior of the jar had burned completely to an ash, although there was a ring of unburned coal all around the inside of the jar about 3 in. thick. This ring of unburned coal probably acted as an insulator for the burning coal within the jar, for being at room temperature, the coal nearest the sides of the jar was at too low a temperature to burn. After removing size 0–$\frac{1}{8}$ from the ovens it was allowed to stand in the container for several weeks, when it was found that it also had started to burn, although the combustion was not as complete as in the former case, and although the rise in temperature while in the ovens was not any greater than had been attained by some of the dry coals which had not taken fire under similar conditions. This series shows,

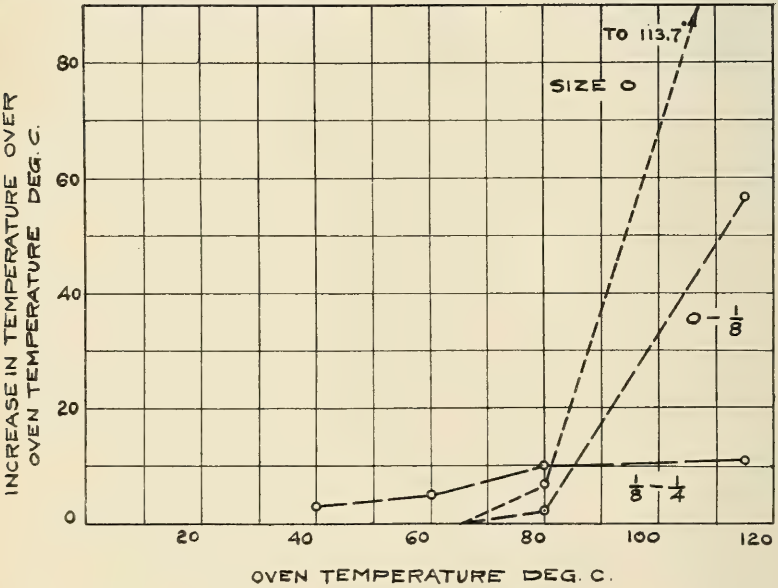

FIG. 7.
SERIES 4—3% PYRITE—WET COAL.

therefore, the effect of having the coal wet and also shows how much more dangerous and how much greater is the liability of a coal to ignite spontaneously if it has been wet. The fact that the coal in this series took fire and that the coal in the preceding series which was of the same composition did not, shows the significance and danger arising from a coal, dependent entirely upon its condition when stored.

Attention is here directed again to the former studies on oxdation by Parr and Francis[1]. In that work it was found that up to a certain point, oxidation continued only so long as the external source of heat continued, but after that point was passed, the oxidation was self-propelling, passing very quickly to the ignition stage. In the powdered sizes and in an atmosphere of oxygen, this rapid oxidation began quite uniformly at about 160°C., and soon thereafter ran up rapidly to ignition. In air, a temperature above 200° was required. This phenomenon is practically duplicated in Series 4, where the zero size of coal, after reaching 193° within the oven, had sufficient elevation to continue in its chemical activity to the ignition point upon being set out into the open air, and thus completed the demonstration of actual burning up of the sample.

Series 5.—Series 5 shows a slightly greater rise in temperature than does Series 3, and, since these two series were exactly the same in all respects except the pyrite content, it seems reasonable to suppose that the greater degree of oxidation, as measured by the rise in temperature, of Series 5 over Series 3 must be attributed in some way to the increased amount of pyrite present. It is true that the increase of temperature rise of Series 5 over Series 3 is not very great, but it is consistent in all the sizes, and as the pyrite content was the only variable in the two systems, the possibility of other factors causing an increase in temperature seems to be excluded.

Series 6.—Series 6 tends to confirm the results obtained in Series 4 in that size 0 again took fire, although size 0–$\frac{1}{8}$ in Series 6 did not show signs of active combustion as did the same size in Series 4; still it sintered together to form a cake, and in all probability would have taken fire had it been allowed to remain in the oven a little while longer. This difference in action of these two sizes in the wet series may be accounted for by the fact that size 0–⅛ in Series 6 may have had a little more water in it than the same size in Series 4, and, so may have taken a little longer time to dry

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[1] Bulletin No. 24, U. of I., Eng. Exp. Sta., June. 1908.

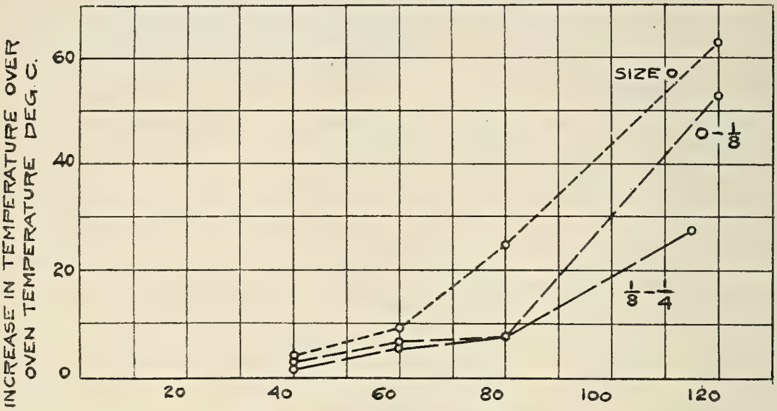

FIG. 8.

SERIES 5—5% PYRITE—DRY COAL.

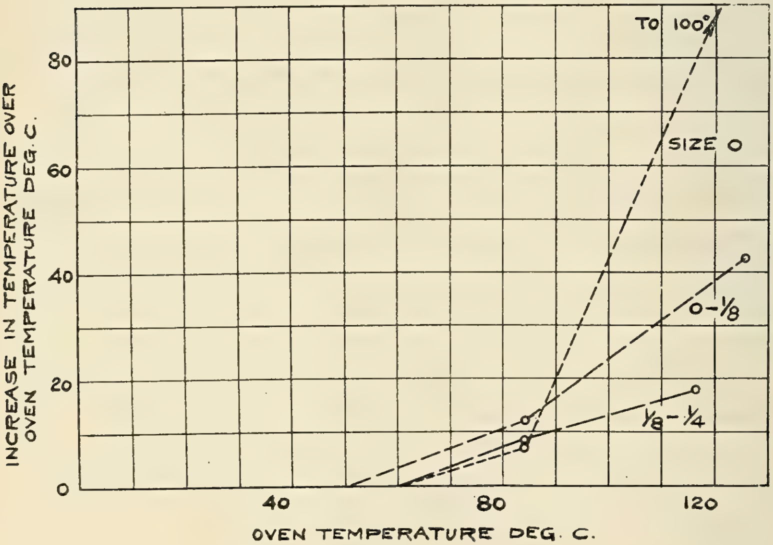

FIG. 9.

SERIES 6—5% PYRITE—WET COAL.

out, thus being in the oven a shorter length of time after it had become dry. For each size an attempt was made to use practically the same amount of water, and in the finer sizes this usually required between four and five liters. In wetting the coal, the water was added slowly with continual stirring, so as to drive out all the air, and the wet coal then had the consistency of a thick slush. The fact that the finest size of Series 4 and 6 took fire, while of the same size and having the same composition, the only difference being that the coal was dry, (Series 3 and 5), did not fire, certainly seems to prove the statements made on page 28 concerning the results of Series 4.

OXIDATION OF SULPHUR AND RESULTING HEAT INCREMENT

To determine how great an oxidation of pyrite took place, the water-soluble sulphur in the fresh coal and the various sizes of oxidized coal was determined. This was done only in Series 2, 4, and 6, where the coal had been wet, for it was thought that the oxidation of the dry pyrite would not be very great. The results are:

Water-Soluble sulphur in the fresh coal....0.0189 per cent.

Water-Soluble sulphur in the oxidized coal:

	Size 0 per cent	$0-\frac{1}{8}$ per cent	$\frac{1}{8}-\frac{1}{4}$ per cent	$\frac{1}{4}-\frac{3}{8}$ per cent	$\frac{3}{8}-\frac{3}{4}$ per cent
Series 2..............................	0.196	0.178	0.0317	0.0231	0.0214
Series 4..............................	0.349	0.340	0.1088		
Series 6..............................	0.744	0.698	0.5520		

Deducting the 0.0189 per cent of water-soluble sulphur originally present in the coal, occurs, as the result of the oxidation:

	Size 0 per cent	$0-\frac{1}{8}$ per cent	$\frac{1}{8}-\frac{1}{4}$ per cent	$\frac{1}{4}-\frac{3}{8}$ per cent	$\frac{3}{8}-\frac{3}{4}$ per cent
Series 2	0.177	0.159	0.0298	0.0212	0.0195
Series 4..............................	0.330	0.321	0.0999		
Series 6..............................	0.725	0.679	0.5330		

If we average the water-soluble sulphur of the two finest sizes, (the coarse dust-free sizes of coal did not retain much of the finely ground added pyrite), and calculate the water-soluble sulphur to pyrite, then we can get a fair estimate of the amount of pyrite that has been oxidized to the soluble ferrous sulphate condition.

	Original Pyrite Content per cent	H_2O Soluble S per cent	H_2O Soluble S Calculated to FeS_2 per cent	Ratio of Calculated FeS_2 to Original per cent
Series 2................	1.65	0.168	0.308	18.7
Series 4................	3.00	0.326	0.612	20.4
Series 6...............	5.00	0.702	1.316	18.8

From the above table, it may be seen that even with widely differing pyritic contents, the amount oxidized was practically constant, for, as shown in the last column of the above table, about 19 per cent of the pyrite present in the coal was oxidized to a soluble condition.

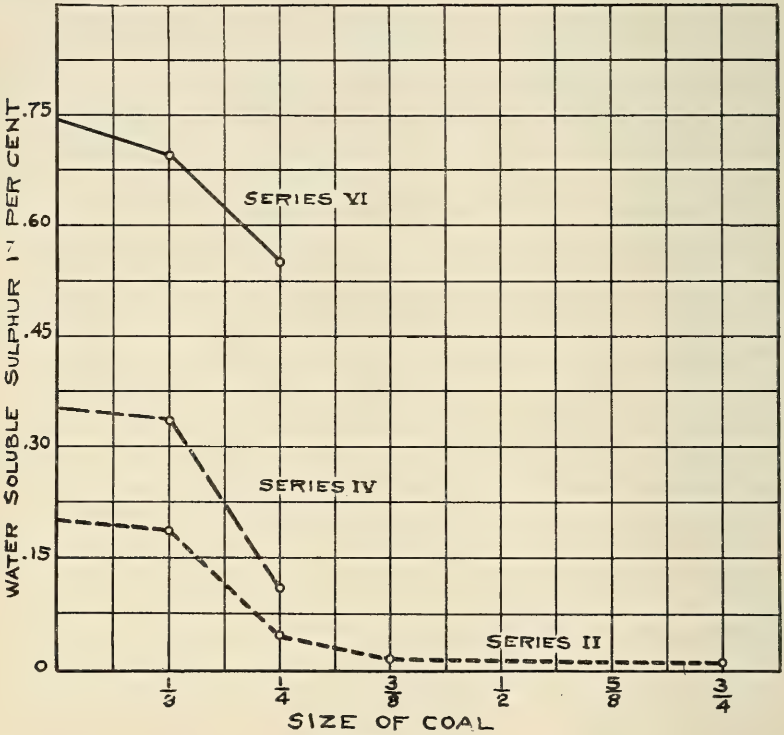

FIG. 10.

SERIES 2—1.65% PYRITE—WET COAL. SERIES 4— 3% PYRITE—WET COAL. SERIES 6— 5% PYRITE—WET COAL.

Having determined the degree of oxidation of the pyrite, it would be interesting to learn how great an increase in temperature would be due to the heat liberated by the oxidation of the pyrite, without taking into consideration the heat liberated by the absorption of oxygen by the carbonaceous material. Pyrite oxidizes according to the following equation:

$$2FeS_2 + 7O_2 + 2H_2O = 2FeSO_4 + 2H_2SO_4 + \text{heat}.$$

It is true that the oxidation goes further: the final product is probably a mixture of ferric sulphate ($Fe_2(SO_4)_3$) and basic ferric sulphate ($Fe(OH)SO_4$), and this would tend to increase the amount of heat liberated. Also, some of the free sulphuric acid formed would combine with some of the basic materials present in the coal, such as lime or alkali, but for the sake of simplicity and to be sure of obtaining a conservative or rather a minimum estimate of the effect of this heat, only the heat liberated in the above reaction was calculated. The data of the heat of formation of the oxidation of pyrite to ferrous sulphate are not yet known; at least a record could not be found in any of the standard physical-chemical authorities, but Somermeier[1] has determined the heat of combustion of pyrite to ferric oxide and sulphur dioxide, so by calculation involving known reactions, the heat liberated in the above equation is found as follows:

$$\begin{array}{rr}
2FeS_2 + 11\,O = Fe_2O_3 + 4SO_2 + 373\text{ K} & (1) \\
2Fe + 3\,O = Fe_2O_3 \qquad + 198\text{ K} & (2) \\
\cline{1-1}
2FeS_2 - 2Fe + 8\,O = \qquad 4SO_2 + 175\text{ K} & (1) - (2) = (2a) \\
4SO_2 + 4\,O + 4H_2O = 4H_2SO_4 \qquad + 256\text{ K} & (3) \\
\cline{1-1}
2FeS_2 - 2Fe + 12\,O + 4H_2O = 4H_2SO_4 + 431\text{ K} & (2a) + (3) = (3a) \\
2Fe + 2H_2SO_4 = 2FeSO_4 + 2H_2 + 94\text{ K} & (4) \\
\cline{1-1}
2FeS_2 + 12\,O + 4H_2O - 2H_2SO_4 = 2FeSO_4 + 2H_2 + 525\text{ K} & (3a) + (4) = (4a) \\
2\,O + 2H_2 \qquad = 2H_2O \qquad + 117\text{ K} & (5) \\
\cline{1-1}
2FeS_2 + 14\,O + 4H_2O - 2H_2SO_4 = 2FeSO_4 \qquad + 642\text{ K} & (4a) + (5) = (5a) \\
\text{or, } 2FeS_2 + 7\,O_2 + 2H_2O = 2FeSO_4 + 2H_2SO_4 + 642\text{ K} &
\end{array}$$

K is used as the symbol for the large calorie, the heat liberated in each of the above equations being expressed in mols of the substance in the reactions. No account is made in this calculation of the heat of solution of the sulphuric acid nor of the hydration of the ferrous sulphate. If the weight of a jar of coal be assumed as 40 lb., (18.12 kilograms), and if the coal contains 5 per cent of pyrite, then it will contain 2 lb. (906 grams), of pyrite. The latter is 19.3 per cent oxidized, then 19.3 per cent of 906 grams will enter into the reaction (or 177 grams). The molecular weight of pyrite is 120, and two molecules entering into the reaction would be 240, hence $\frac{177}{240}$ x 642 K, or 473 K will be obtained as the heat liberated by the oxidized pyrite in 40 lb. of coal. The specific heat of the coal used is not known, but some rough experiments by Threlfall[1] show that the specific heat of bituminous coal varies from 0.3 to 0.45, with the average at about 0.35. If the specific heat of the coal used be assumed as 0.35, then the heat generated by the oxidation of the pyrite would be sufficient to raise the temperature of the coal

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[1] Jour. of the Am. Chem. Soc., Vol. 26, p. 566.

NOTE.—He finds that 1 gram of sulphur in the form of FeS_2 yields 2915 calories. Then, 2 gram-mols of FeS_2 would yield 2915 x .533 x 240 = 373 large calories.

$\frac{473}{18.12 \times .35}$ or 74.5°, which, it may be seen, is sufficient in amount to account for the larger part of the increase as indicated by the curves. Threlfall calculated the heat of oxidation of pyrite from one of Richter's experiments, the data of which were available. He also calculated the heat of oxidation of the carbonaceous material from the loss of hydrogen and carbon during the oxidation. In this experiment, the coal was heated to a temperature of 190°C. for ten hours in a slow stream of air. The oxidation of the pyrite gave enough heat to give a rise in temperature of 175°, and the oxidation due to absorption of the oxygen gave a rise of 750°, about four times as much. From these data, the total heat evolved from the pyritic oxidation does not seem important when compared with the heat liberated by the absorption of oxygen, but it is to be remembered that the absorption of oxygen by coal is immensely accelerated at an increased temperature, and it seems very probable that the pyritic oxidation may be the means by which this temperature, favorable to active oxygen absorption, is attained.

As has been shown by the work of Parr and Francis,[2] the temperature at which oxidation of the coal substance itself actually begins (about 120° in oxygen and 135° in air) is comparatively low, and therefore any influence which would serve as a force to bring the coal up to this temperature should be taken into account. Since coal is a rather poor conductor of heat the major part of the heat generated within the pile will be retained, and from the calculation of the heat generated by the pyritic oxidation, it may be seen that a sufficient quantity of heat was liberated to bring the coal up to this temperature of 135°, at which active oxidation of the carbonaceous materials begins. Of course the rise in temperature of a coal pile in storage up to 135° should not be ascribed to the effect of the pyritic oxidation alone, for it is the result of the heat liberated by the oxidation of both the coal and the pyrite. The above, however, was merely given as an example to show how great the effect of the pyritic oxidation may be.

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[1] Jour. of the Soc. of Chem. Ind., Vol. 28, p. 763.

[2] Engineering Experiment Station, University of Illinois, Bulletin No. 24.

Since the above experiments show that the oxidation of the pyrite is practically constant, that is, about one-fifth of the total pyrite present, then it follows that coals with increasing pyrite contents will have a corresponding increase in pyritic oxidation and a correspondingly greater amount of heat will be liberated. The result is a hastening of the rise in temperature up to the critical point at which the absorption of oxygen by the coal itself is rapid enough to increase the temperature up to the point of self ignition. This seems to be the explanation of the ignition of Series 4 and 6 which were identical in composition, size, and method of treatment with Series 2, except that the former contained a quantity of pyrite sufficient to cause the coal to ignite, whereas in the latter series the quantity of pyrite present was not great enough to cause this initial rise in temperature up to the critical point at which no external impetus is necessary.

It is to be remembered, of course, that in actual storage the pyritic oxidation will proceed much further than one-fifth of the total pyrite present, as in these particular experiments, but the fact still remains that the degree of pyritic oxidation in coals of various pyrite content is in direct proportion to the pyrite content so long as similar conditions of storage are maintained. It is true, certain coals containing practically no pyrite ignite spontaneously, although from the above work it is reasonable to suppose that an increased amount of pyrite would hasten the ignition. Again, the particular coal worked with did not ignite spontaneously under any conditions until the pyrite content was increased.

It seems, therefore, that the presence of pyrite is a much more important factor in the spontaneous ignition of coal than has heretofore been ascribed to it, and its influence on the spontaneous combustion of coal cannot be discarded in the off-hand way that has been so common with some of the previous investigators, merely because of the fact that some coals containing no pyrite at all would ignite spontaneously.

DETAIL OF ANALYTICAL PROCESSES FOR OXIDIZED SULPHUR

Knowing that Illinois coal contains more or less calcium sulphate, which would partly go into solution and be included in the water-soluble sulphur, it was decided to determine the ferrous sulphate actually present in the fresh coal and also the other sulphur compounds. This necessitated a complete analysis of the ash of the coal, and with the exception of the determination of the alkalies and chlorine, this analysis was made. From other analytical work on coal done in this laboratory it is known that chlorine and sodium and potassium exist in small quantities in the coal, but as the amount of chlorine present is such as to practically neutralize the alkali and, since their presence has no direct bearing upon the work at hand, these constituents were not determined.

For the analysis of the ash, two samples of 10 grams each of coal were used. These were ashed in a platinum dish, then sodium carbonate was added and the fusion completed. The fusion was put in a casserole and dissolved in boiling water, acidified with hydrochloric acid and dehydrated. The analysis was then carried out in the same manner as for any exact silicate rock analysis, with two dehydrations, volatilization of the silica with hydrofluoric acid, etc.

For the determination of iron and aluminum, the filtrate from the above,—along with the residue from the silica determination, which had been fused with potassium pyrosulphate was made alkaline with ammonia. The precipitate of the mixed hydroxides was thoroughly washed and then redissolved in hydrochloric acid, and then was made up to 250 c. c. In 50 c. c. of this solution, the iron was determined volumetrically by the Zimmermann-Reinhardt method. The other 200 c. c. were then reprecipitated with ammonia and weighed.

The calcium was determined by precipitating it as the oxalate, dissolving in sulphuric acid and then titrating with standard potassium permanganate. The magnesium was determined as the pyrophosphate. Since many of the Illinois coals also contain some calcium and magnesium carbonates, the carbon dioxide liberated from the coal by means of boiling 1:2 sulphuric acid was determined in the improved form of the Parr total carbon apparatus[1].

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[1] Eng. Exp. Sta. Uni. of Ill., Bull. No. 37 shows diagram of the apparatus,

The results of the above analyses calculated in per cent of the original air-dry coal are as follows:

	Per cent	Per cent
Silica (SiO_2)	6.108	6.055
Ferric Oxide (Fe_2O_3)	1.432	1.477
Aluminum Oxide (Al_2O_3 also any P_2O_5 and TiO_2)	2.108	2.223
Calcium Oxide (CaO)	1.576	1.571
Magnesium Oxide (MgO)	0.123	0.117
Carbon Dioxide (CO_2)	0.876	0.851

Numerous methods for the determination of the water-soluble iron, that is, iron in ferrous sulphate, were tried. Among these might be mentioned, digesting the coal with water both hot and cold for a period of one or two hours and also over night, using dilute hydrochloric and sulphuric acid in concentrations varying from two drops per 300 c. c. H_2O up to as high as 2 per cent acid. All these methods, however gave discordant and unreliable results.

The method finally adopted, which seemed to give the best results and which minimized the possibility of oxidation, was as follows: Three samples of 25 grams of finely ground air-dry coal were placed in large folded filter papers. About 600 c. c. of well boiled distilled water, which was practically free from air and carbon dioxide, was poured over each sample, the latter being well stirred so as to wet the fine coal thoroughly. The filtrate was then poured back over the coal, and the next filtrate, consisting of the same water as first used, was again poured back on the coal, thus making three leachings with the same water. The coal was finally washed with an additional 100 c. c. of boiling water and the total filtrate then brought to boiling. Five drops of stannous chloride solution were added, the liquid was chilled, an excess of mercuric chloride was added, and in five minutes the mixture was titrated with potassium permanganate. A blank of an equal amount of boiling, distilled water was run through the same procedure. The three titrations, which were made from a burette calibrated by the Reichsanstalt, and which was used for all volumetric work, varied 0.13 c. c. from the lowest to the highest. The results calculated to per cent of air-dry coal were:

0.0059 per cent Fe=0.0160 per cent $FeSO_4$=0.0034 per cent S. The water-soluble sulphur directly determined was equal to 0.0189 per cent, and as calculated above from the water-soluble iron was 0.0034 per cent. The difference of these two values 0.0189—0.0034 or 0.0155 per cent is some form of water soluble sulphur other than ferrous sulphate.

The next step was to determine the calcium sulphate present. This was attempted in three ways: first, since one part of calcium sulphate is soluble in about 500 parts of water, it was decided to dissolve out the $CaSO_4$ by digesting the coal with a large volume of water; second: the calcium sulphate was changed to calcium carbonate and sodium sulphate by the addition of sodium carbonate; and third, since gypsum is soluble in hydrochloric acid, a 10 per cent solution of the latter was added to the coal.

Duplicate samples of 25 grams each of coal were treated as outlined above and were put on the water bath over night. The next day they were filtered and the sulphur carefully precipitated with barium chloride after the filtrates had been concentrated. The results of the six determinations are as follows:

First Method Boiling Water	Second Method 2 per cent Na_2CO_3 Solution	Third Method 10 per cent HCl
0.0192 per cent S	0.0569 per cent S	0.0373 per cent S
0.0187 per cent S	0.0571 per cent S	0.0211 per cent S

The third method with its large variation may be discarded at once, for it seems that the solubility of the gypsum in the acid is not exact or reliable. The first method gave concordant results, but as compared with the second method they are much too low. It is very probable that after a long period of digestion the first and third methods would both give all of the $CaSO_4$ present, but as the data show, 10 hours' digestion at 100° is not sufficient. The second method gives results probably as nearly correct as can be obtained, although the solubility of calcium carbonate, which is about 50 parts in a million, would create a slight error. The sulphur obtained by the second method (as it would be from any of the three methods outlined) is, therefore, the sulphur from the ferrous and calcium sulphates. The sulphur in the ferrous sulphate, however, was determined by calculation from the water-soluble iron. The difference between these two values would, therefore, give us the sulphur present as calcium sulphate. Tabulating these results, we have:

			Per cent
H_2O soluble S calculated from H_2O soluble Fe			0.0034
H_2O soluble S directly determined			0.0189
H_2O soluble S plus S in $CaSO_4$ (Na_2CO_3 method)			0.0570
	1.186		
Total S in coal	1.156	Average	1.1697
	1.167		
S in Pyrite			0.7470

S in $CaSO_4$ = S as ($FeSO_4$+$CaSO_4$) — S as $FeSO_4$

= 0.0570—0.0034 = 0.0536 per cent

0.0536 per cent S = 0.228 per cent $Ca\ SO_4$

0.0034 per cent S = 0.0160 per cent $Fe\ SO_4$

$Fe\ SO_4$ = 0.0160 per cent = 0.0034 per cent S

$Ca\ SO_4$ = 0.228 per cent = 0.0570 per cent S

FeS_2 = 1.397 per cent = 0.7470 per cent S

Total Sulphur determined..................0.8074 per cent

Total Sulphur in coal.....................1.1697 per cent

Sulphur unaccounted for and probably
existing as organically combined S.....0.3623 per cent

Since the coal used contained 0.863 per cent of carbon dioxide which was liberated on the addition of acid, this carbon dioxide must therefore exist in the original coal in the carbonate condition, very probably as the carbonates of calcium and magnesium. 0.864 per cent of CO_2 is equivalent to 1.965 per cent of $CaCO_3$. The calcium oxide (CaO) as determined in the ash analysis was 1.574 per cent, which is equivalent to 2.807 per cent of $CaCO_3$.

The difference between these two values, 2.807—1.965 = 0.842 per cent of calcium measured in terms of calcium carbonate, is unaccounted for and probably exists as calcium silicate and calcium sulphate.

The above has all the CO_2 calculated to $CaCO_3$, but in reality the coal contains 0.120 per cent of magnesium oxide (MgO), which probably exists as the carbonate, so 0.120 per cent MgO is equivalent to 0.251 per cent $MgCO_3$ or 0.131 per cent CO_2. Deducting this CO_2 from the total CO_2, it would give the CO_2 equivalent to $CaCO_3$.

0.863 per cent total CO_2
0.131 per cent CO_2 equivalent to MgO and $MgCO_3$

0.732 per cent CO_2 which is very probably all $CaCO_3$
0.732 per cent CO_2 = 1.665 per cent $CaCO_3$
Total $CaCO_3$ from CaO = 2.807 per cent
Total $CaCO_3$ from CO_2 = 1.665 per cent

1.142 per cent of $CaCO_3$ existing as $CaSO_4$ and $CaSiO_3$.

$CaSO_4$ as determined = 0.228 per cent equivalent to 0.167 per cent of $CaCO_3$.

1.142 per cent—0.167 per cent = 0.975 per cent $CaCO_3$ existing as $CaSiO_3$.

0.975 per cent $CaCO_3$ is equivalent to 1.112 per cent $CaSiO_3$.

Summing up the above combinations:

$MgCO_3$...	0.251	per cent
$CaCO_3$....	1.142	per cent
$CaSO_4$....	0.228	per cent
$CaSiO_3$....	1.112	per cent
$FeSO_4$....	0.0160	per cent
FeS_2....	1.397	per cent

The remainder of the iron and silica in the ash is probably present as earth or basic iron silicates with some free silica. The ultimate analysis of the ash sums up to 11.387 per cent. The ash, as determined from an average of four determinations, (varying 0.070 per cent from highest to lowest) is 12.030 per cent; the difference of 0.643 per cent is alkali, chlorine, and probably a small amount of combined carbon dioxide, for the ash was determined by blasting to a constant weight in a porcelain crucible and was not carried to complete fusion in platinum.[1]

From the data presented, it may be seen that the oxidation of pyrite in fresh lump coal is very slight, and that the sulphur obtained as water-soluble sulphur consists of the mixed sulphates of iron and calcium. The meaning of the term water-soluble sulphur is, therefore, necessarily vague, unless the conditions of its determination are clearly kept in mind. The solubility of calcium sulphate is great enough to cause discrepancies in the results and lead to fallacies in conclusions, unless care is taken to have conditions of determination, such as volume of water used for leaching and length and temperature of digestion always the same. Then it can be assumed, with reasonable safety, that the water-soluble sulphur determinations will all contain equal amounts of calcium sulphate. For the determination of ferrous sulphate, the determination of water-soluble iron would be the best, if the leaching is done quickly with well-boiled distilled water. The practice of digesting the coal with water for any length of time should be discouraged, for oxidation will surely set in, giving, of course, an error.

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[1] Bulletin No. 37, U. of I. Eng. Exp. Sta., Parr and Wheeler, August, 1909.

ADDITIONAL EXPERIMENTS ON MIXED SIZES OF COAL

Series 7, 8 and 9.—Having studied the effect of different pyrite contents on various sizes of coal under different conditions of moisture and temperature, it was decided to study the influence of these variables on a mixture of these sizes. For this purpose the coal was used directly as it came from the crusher; Series 7, 8 and 9 contained 1.4 per cent, 3 per cent and 5 per cent, respectively, of pyrite. The resulting rise in temperature of the wet and dry samples is shown in Fig. 11, 12 and 13. Fig. 14 is a comparative study of the three dry samples of each series, and Fig. 15 shows a similar study of the wet samples.

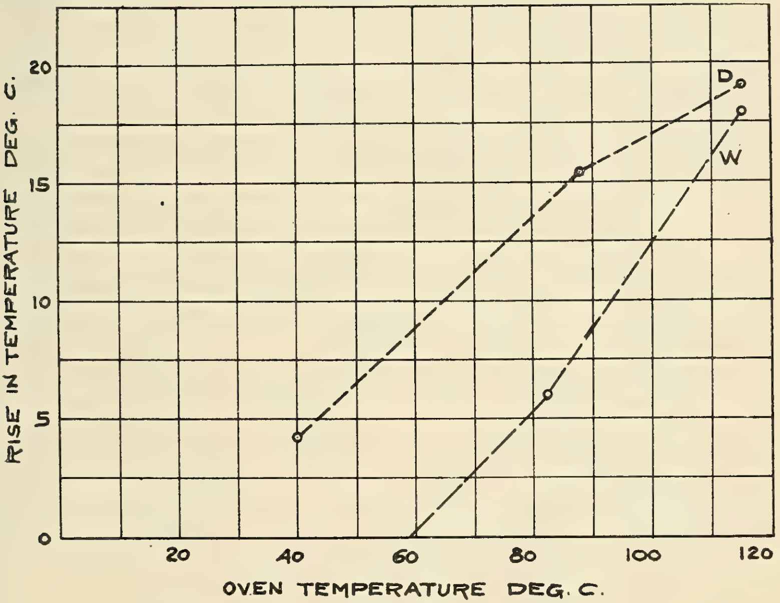

FIG. 11.

SERIES 7—1.4% PYRITE—DRY AND WET COAL.

On account of the increased amount of the larger sizes of coal in these series, the rise in temperature of the coal over the oven temperature did not approach that of some of the fine sizes of the

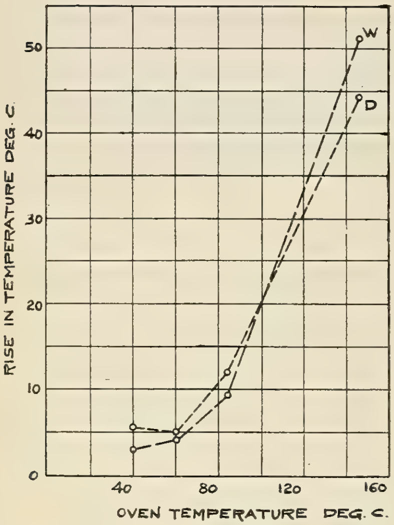

FIG. 12.
SERIES 8—3% PYRITE—DRY AND WET COAL.

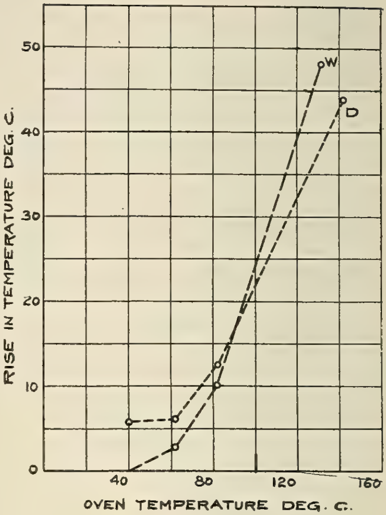

FIG. 13.
SERIES 9—5% PYRITE—DRY AND WET COAL.

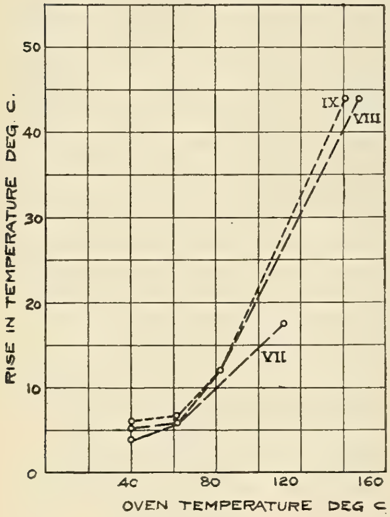

FIG. 14.
SERIES 7, 8, 9—1.4%—3%—5%-PYRITE—DRY COAL.

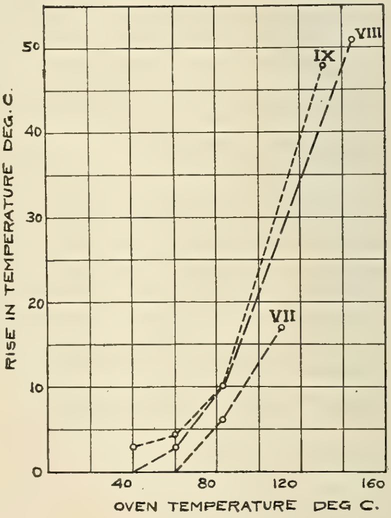

FIG. 15.
SERIES 7, 8, 9 —1.4%—3%—5%-PYRITE— WET COAL.

preceding series, but it is seen how much greater the rise in temperature of Series 8 and 9, with their greater pyritic content is over that of Series 7. This is corroborative of the facts disclosed and discussed in the preceding series, and needs no further comment, for Fig. 11 to 15 showing the results are self-explanatory. It may be argued that Series 8 and 9 showed such a marked rise over Series 7 because the oven temperature of the last oven was about 10° higher in Series 8 and 9 than it was in Series 7. This was because of a rather serious accident in the storage battery room which was of such a nature that it could not be remedied without interruption, and so spoiled Series 8 and 9; hence an attempt was made to maintain practically the same temperature as before by reducing the number of heating lights. It hardly seems reasonable, and it might be said, it is almost impossible, that an increase in oven temperature of 10° should cause an increase of the rise in temperature of about 30°, so the only variable left that could cause such a rise is the difference in pyritic content. Why this difference in behavior of these three series, which were identical in composition, size and method of treatment, should be so marked has been shown above; and all that needs to be added is that these series substantiate the results of those preceding.

A STUDY OF POSSIBLE DETERRENTS

Series 10.—Since the relative importance and the influence of the different variables under various conditions seem to have

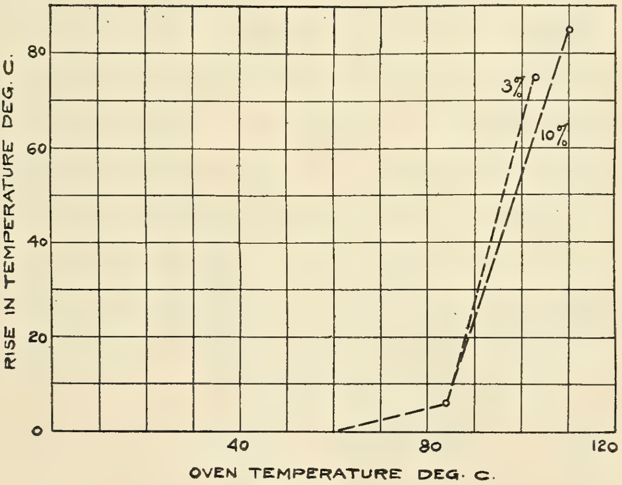

FIG. 16.

SERIES 10—5% PYRITE—SIZE 0-$\frac{1}{8}$—3%, 10% NaCl SOLUTION.

been fairly well established, it is natural that an attempt should be made to remove, if possible, this property of self ignition from a mixture of coal that had been known to take fire. As has been explained before, size $0-\frac{1}{8}$, containing 5 per cent pyrite, was decided upon. This size of coal was thoroughly wet with different strengths of various solutions. The 3 per cent solution contained 30 grams of the salt per liter, and the 10 per cent solution contained 100 grams of the salt per liter.

The coal in Series 10 was wet with a solution of sodium chloride so as to study the effect of an inert salt, that is, inert so far as undergoing any reaction with the coal is concerned. This would, therefore, be practically the same as increasing the ash content. Fig. 16 shows that this addition of common salt exerted no retarding influence on the oxidation of the coal, the rise in temperature of the series being about 70°.

Series 11.—A solution of calcium chloride was then used. This salt is very hydroscopic and absorbs moisture with avidity and also retains it, so that it is difficult to dry anything saturated with it. The 3 per cent solution showed no retarding influence, whereas the action of the 10 per cent solution was very marked (see Fig. 17). In the latter case, a rise in temperature of only 26° took place, which shows that a solution of this strength retarded the oxidation very materially. This presumably was not because of any action inhibiting oxidation itself, but merely because so much heat was used in driving off the water.

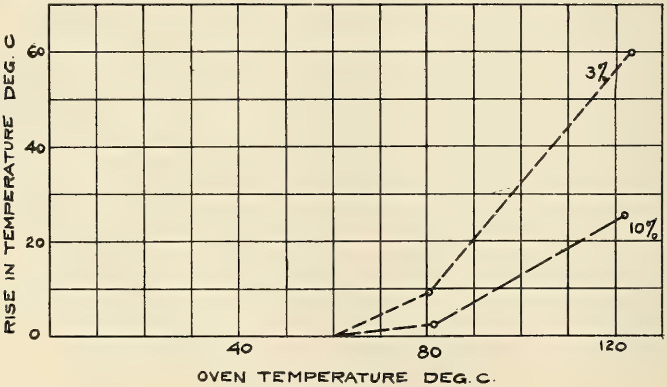

FIG. 17.

SERIES 11—5% PYRITE—SIZE $0-\frac{1}{8}$—3%, 10% $CaCl_2$ SOLUTION.

Series 12.—Fig. 18, Series 12 shows the action of a basic substance, for in this series a saturated solution of lime water was used. The rise in temperature was not retarded to any great extent. Lime water was used to see if it would not reduce the oxidation of the pyrite, because in the weathering of the latter substance, a considerable amount of free sulphuric acid is formed. The acid would then combine with the calcium hydroxide to form calcium sulphate. A film of calcium sulphate would then cover every particle of pyrite and thus prevent further oxidation. It was hoped that this action would take place and so keep the temperature down, but the rise in temperature was greater than it was thought it would be, probably because of the heat liberated by the neutralization of the base by the acid.

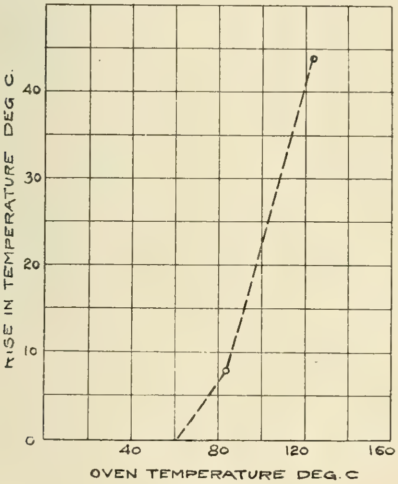

FIG. 18.

SERIES 12—5% PYRITE—SIZE 0-⅛—Ca(OH)$_2$ SOLUTION.

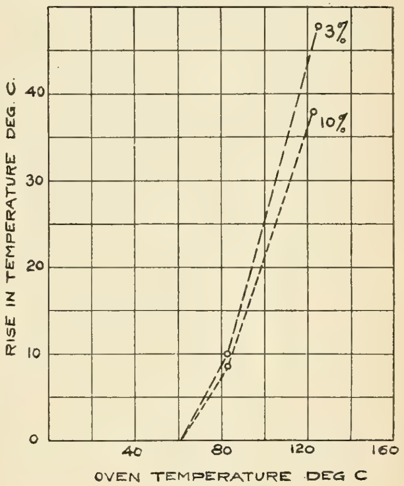

FIG 19.

SERIES 13—5% PYRITE—SIZE 0-⅛—3%, 10%, Na H CO$_3$ SOLUTION.

Series 13.—Since even a solution of sodium bicarbonate, when boiled, gives off carbon dioxide, the effect of its decomposition under a higher temperature was next studied. Also, the sodium carbonate formed would make the coal alkaline and so remove any free acid formed. As seen in Fig. 19, the 10 per cent solution has quite a retarding influence, due in all probability to the absorption of carbon dioxide by the coal instead of oxygen, and so the oxidation is lessened. It is very probable that after some time the coal would be oxidized to the same degree that it would be if the $NaHCO_3$ and CO_2 were not present, but the presence of a large amount of carbon dioxide decreases the speed of oxidation, extends the oxidation process over a longer period and so keeps the temperature down to a safe degree.

Series 14.—Ferrous sulphate oxidizes readily and quickly to ferric sulphate and basic ferric sulphate. It was thought that if a considerable amount of ferrous sulphate were added to the coal, it would be oxidixed before the coal and retard the oxidation of the latter. This was probably the case, but the heat liberated by the oxidation of the ferrous sulphate just about neutralized its retarding influence, so that the final effect was nearly the same as if the coal had been wet with pure water instead of the ferrous sulphate solution. As seen in Fig. 20, the coal wet with a 10 per cent solution gave a greater rise than that wet with a 3 per cent solution, the difference in rise of temperature probably being due to the heat liberated by the oxidation of the excess of 7 per cent of ferrous sulphate.

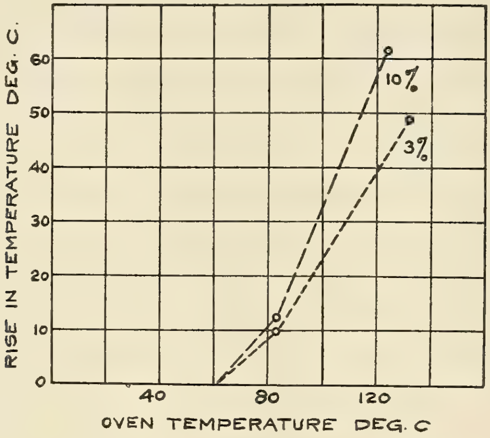

FIG. 20.
SERIES 14—5% PYRITE—SIZE 0-$\frac{1}{8}$—3%, 10% $FeSO_4$ SOLUTION.

From the above work, it may be seen that the 10 per cent solutions of calcium chloride and sodium bicarbonate retard the oxidation of the coal considerably, although whether or not a commercial application of the facts disclosed in this work on small amounts of coal is practicable or not is still to be learned from work on large storage units. Since both of these chemicals are fairly cheap, the idea seems reasonable and warrants further investigation.

Series 15.—In this series an attempt was made to determine the effect of intermittent heating and cooling, on the theory that the result of the preliminary heating would bring about those oxidation processes, which, by their cumulative effect, push the temperature up to the danger point, but, when once effected, might not be operative a second time. Three samples were thus tried out: one, (A) of mixed sizes, the same as in Series 10 to 13, with the normal amount (1.45 per cent) of pyrite present; another, (B) designated as 0–$\frac{1}{8}$ size; and the third, (C) a very fine coal dust, obtained by grinding to an impalpable powder in a ball mill. The temperature maintained by the last oven for the first or preliminary heating was 135° to 140°, with a view to carrying the oxidation along to a considerable extent, yet well short of the point of ignition. After cooling and bringing the mass up to the same temperature for the second heating, a more severe test would result than if a lower oven temperature were used. This plan was followed with all but the first sample, which had a preliminary oven-temperature of 120°. The subsequent heating, however, was carried to 140°.

The results of these tests are given in Table 17, page 22. Briefly reviewed, the results are as follows: In the first heating of the oven containing the mixed sizes, (sample A), to 120°, the coal temperature rose 43° above the oven temperature; in the second heating, the coal temperature increased only 11° above the oven temperature, even though the oven temperature was 15° higher in the second heating than in the first. Had the first heating also been up to 135°, the rise in coal temperature would have been greater than 43°, and the difference in the rise of the coal temperature over oven temperature of the two heats would also have been greater. However, the marked retarding effect of preheating is well shown in this test.

In the size 0–$\frac{1}{8}$ coal, (sample B), the difference in temperature increase between the first and second heating is much greater, due ot the finer size of coal used and also because the oven temperature in both heats was practically the same, the increase for the first heating being 70° and for the second heating only 19° or a difference in the rise in temperature amounting to 51°.

The very fine coal dust from the ball mill, (sample C), rose to 205° within 48 hours after having been put into the 60° oven. Since the ventilation of the oven was insufficient to carry off the heat as quickly as it was generated, it was impossible to keep the oven temperature down to 60°, the thermometer standing at 69°. The fact that the coal, however, maintained this oven temperature of itself even though a great amount of heat was being continually lost because of the ventilating system, shows how large an amount of oxidation took place. After cooling for 3 days and then reheating at 60°, the coal temperature rose to 73° in an oven temperature of 64°, causing only a 9° rise, whereas in the first heating at this temperature a 136° rise took place. The coal was then placed in the high temperature oven, and this oven was then heated up to 147° for three days. At the end of this time, the coal temperature was 220°, a rise of only 73° over the oven temperature. If this coal had been put into this oven first, without preheating, it would undoubtedly have taken fire at once, i. e., in 24 or 36 hours. However, as it was, the coal did not take fire until it was removed from the oven and exposed to the air. The fact that the coal did take fire after removing it from the oven shows that the time of oxidation (3 days) in the oven was not great enough to allow a thorough oxidation, although the behavior of the coal in the first two heats at 60° is of immense value in showing the effect of preheating. This particular sample of coal, ground as fine as it was, represents of course an exaggerated condition, not likely to be found under practical conditions of storage, but it was used to illustrate clearly the effect of preheating, which was shown so strikingly when the coal first indicated a rise in temperature of 136° at 69° oven temperature and then showed a rise of only 9° the second time it was heated to that temperature. It should be noted also that in the third heating, the oven temperature was sufficiently high to produce that type of oxidation which results in the formation of CO_2. This, with the marked property of condensation or occlusion of oxygen by the very finely-divided material, would be expected to result in a marked increase of temperature, quite distinct from what would occur with an oven temperature of only 60°.

To show the results on these three samples in a diagrammatic form, an attempt is made in Fig. 21, wherein the heat area is divided in the center. Points representing the increase of temperature in the first or preliminary heating are located in the left-hand area and the points representing the increase of temperature during the second heating are located in the right-hand area. In order, then to show the relation as to differences of increase, the points for the same coal in the two areas are connected by a straight line.

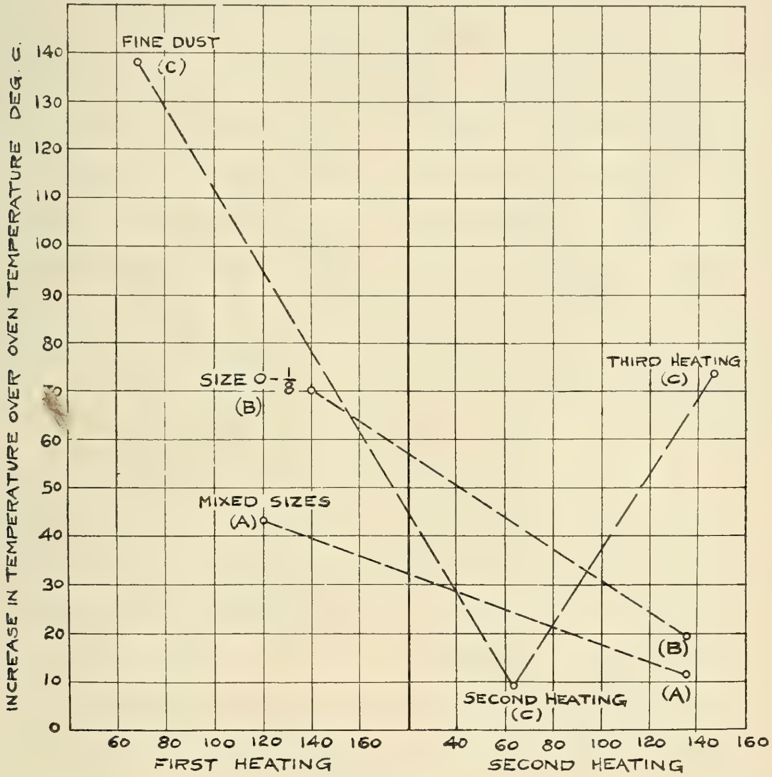

FIG. 21.
SERIES 15.

ADDITIONAL DATA

Railway Storage of Coal.—On account of the general strike of bituminous coal miners in the early spring of 1910, many of the large users of coal, such as the railroads, stored large quantities of coal for future use. In reply to a circular letter sent out for the purpose of gathering data and information concerning this coal in actual storage, Mr. P. Maher, Superintendent of Motive Power of the Chicago and Alton Railroad Company, reports as follows. A pile containing 2250 tons, 6 ft. high, 300 ft. long and 8 ft. wide, of run-of-mine, Springfield district coal, stored at Slater, Illinois, 1½ months after storage, showed 30 per cent slack, and the company was not getting results from the storage coal such as were obtained from similar coal fresh from the mine. A pile of the same kind and size of coal stored at Brighton Park, Illinois, containing 3300 tons, crumbled into 20 per cent of slack. This pile was 6 ft. high, 372 ft. long and 41 ft. wide. A pile of similar coal stored at Ridgely, Illinois, containing 19 710 tons, showed 35 per cent of slack and took fire in several places. This pile was 10 ft. high, 330 ft. long and 80 ft. wide. The reason that the latter pile took fire and the former two did not was probably due to the increased height. It is to be noted that the first two piles were 6 ft. high, while the third was 10 ft. Also, the first two piles were 8 and 41 ft. wide, respectively, while the third was 80 ft. wide. Presumably, in the first two cases, the radiation of heat in the initial stages was sufficient to keep the rise in temperature from reaching the point where the more active processes were set in motion.

IV. Conclusions

1. The oxidation of coal is continuous over a wide range of time and conditions, and begins with the freshly-mined coal at ordinary temperatures. A number of oxidation processes are involved, which are more or less distinct in character, some being relatively slow and moderate in form, while others are rapid and vigorous in their action.

2. In general it may be said that for a given coal a point exists, as indicated by the temperature, below which oxidation is not ultimately destructive. The continuance of this point is dependent upon certain accessory conditions; if these conditions are withdrawn, the oxidation ceases. On the other hand, above this critical point, which is best indicated by temperature, oxidation is ultimately destructive and is characterized by the fact that it does not depend for its continuance upon external conditions, but is self-propelling or autogenous.

3. The point of autogenous oxidation, while varying for dif-

ferent conditions, may be indicated by temperatures of the mass ranging from 140° to 160°C., in an atmosphere of oxygen, or approximately between 200° to 275°C. in oxygen diluted with nitrogen, as in air, depending to a great extent upon the fineness of division. The phenomenon of fire or actual kindling does not occur until a much higher temperature is reached, usually beyond 350°C.

4. The temperature at which autogenous oxidation begins is the sum of numerous temperature components, each one of which, either because of its own contribution to the total heat quantity or because of its function as a stimulus for chemical activities, must be looked upon as a dangerous factor, tending directly to the ultimate result of active combustion throughout the mass. An enumeration of the more important elements which contribute towards this end are the following:

a. External Sources of Heat.—Oxidation, especially of the lower or moderate form, is greatly accelerated and in certain phases directly dependent upon an increase of temperature. What may be external or physical sources of heat, and thus presumably avoidable, are suggested by the following:

(*1*) Contact of the mass with steam pipes, hot walls or floors under which are placed heat conduits of any sort.

(*2*) The heat of impact or pressure due to the method of unloading or to the depth of piling.

(*3*) Climatic or seasonal temperature at the time of storage.

(*4*) The direct absorption of heat from the sun or from reflecting surfaces.

b. Fineness of Division.—Coal in a fine state of division presents a very much larger surface and brings a much larger quantity of reacting substances in contact with oxygen than when in solid masses. Under these conditions, with a condensation or accumulation of relatively large amounts of oxygen immediately surrounding or in contact with the particles of carbonaceous matter, the circumstances are exceedingly favorable for rapid oxidation upon the arrival of the mass to a suitable temperature. But more especially does this fineness of division facilitate the initial form of oxidation described under *c* below.

c. Easily Oxidizable Compounds.—A first or initial stage of oxidation exists in bituminous coals which does not result in the formation of CO_2. There are present in coals of this type, unsaturated compounds, which have a marked avidity for oxygen at ordinary temperatures, the products being humic acid or other fixed constituents of the coal texture. Coals vary widely in this respect, and it has been proposed by some to regard this property as an index of the liability to spontaneous combustion. It is, however, very largely dependent upon the freshness of the coal and upon the fineness of division, (see *b* above,) and should be looked upon as a contributing factor, though in coals of the Illinois type, at least, with their high per cent of sulphur, this action should doubtless be considered second in importance to that of iron pyrites.

d. Iron Pyrites.—The presence of sulphur in the form of iron pyrites is a positive source of heat due to the reaction between sulphur and oxygen. This may be conveniently referred to as the second stage in the process of oxidation. Here again rapidity of oxidation is directly dependent upon fineness of division. Since coals, as a rule, have a much higher earthy or ash content in the fine duff, and since iron pyrites is a large component of this material, it follows that the presence of dust or duff in all coals of the Illinois type is a positive source of danger. Since coals of the Illinois or mid-continental field have in the larger number of cases iron pyrites averaging over 6 per cent, or, as sulphur above 3 per cent, the heat increment from the oxidation of only $\frac{1}{5}$ of this material is sufficient to raise the temperature of the mass approximately 70°, assuming that there is no loss by radiation. Under usual conditions, and especially considering the greatly accelerated rate of chemical activity accompanying a rise of temperature, this oxidation may proceed with such rapidity that the heating up of the mass will be but little affected by loss of heat due to radiation, except in relatively shallow piles.

e. Moisture. Moisture, while essential to pyritic oxidation, is given separate mention because its importance is apt to be underestimated. Any coal with conditions favorable to oxidation will be facilitated in that action by moisture. It is to be noted in this connection that the normal water content or vein moisture of coals in this region is rarely below 10 per cent and ranges usually from 12 per cent to 15 per cent. The presence of such water must be borne in mind in considering the likelihood of chemical activity on the part of the pyrites present. Without exception, in all the series of tests, *the wetting of the coal increased the activity as shown by the ultimate temperature.*

f. The Oxidation of Carbon and Hydrogen. A third stage of oxidation of the carbonaceous material exists by reason of the tendency of certain of the hydrocarbon compounds of coal to oxidize with the formation of CO_2 and H_2O at temperatures in excess of 120° to 140°. Though this type of oxidation does not take place appreciably at ordinary temperatures, it must be looked upon as an exceedingly dangerous stage in the process of oxidation, owing to the very much higher quantity of heat which is discharged by the oxidation of carbon and hydrogen; so that the temperature of autogenous action, though ordinarily occurring at a higher point by 100° or more, may be quickly attained as a result of this form of oxidation. Any initial heat increments, therefore, which threaten to bring the chemical activities along to the point where the oxidation processes invade the carbonaceous material in this manner must be looked upon as dangerous. For example, any of the initial or contributory processes which result in raising the temperature of the mass 50° above the ordinary temperature, would, in all probability, have enough material of the sort involved in such action to continue the activity until another 50° had been added, which would thereby attain to the condition wherein this third type of oxidation would begin.

g. The fourth stage of oxidation may be indicated as occurring at temperatures above 200° to 275° and differs from the previous stages in that the action is autogenous and not dependent upon other sources of heat to keep up the reacting temperature. Activity in this stage is further accelerated by the fact that above 300° the decomposition of the coal begins, which is exothermic in character, thereby contributing somewhat to a further increase in temperature. The ignition temperature is reached at a point still further along, usually in excess of 300° to 400°C.

5. The above formulation of the various stages and types of oxidation clearly indicates the principles which must be observed in any attempt at the prevention of spontaneous combustion. The following enumeration, therefore, of preventative or precautionary measures is to be considered as suggestive rather than complete in character.

a. The avoidance of an external source of heat which may in any way contribute toward increasing the temperature of the mass is a first and prime essential.

b. There must be an elimination of coal dust or finely-divided material. This will reduce to a minimum the initial oxidation processes of both the carbonaceous matter and the iron pyrites. These lower forms of oxidation are to be looked upon as forces, without which it would be impossible for the more active and destructive activities to become operative.

c. Dryness in storage and a continuation of the dry state, together with an absence of finely-divided material, would practically eliminate the oxidation of the iron pyrites.

d. Artificial treatment with specific chemicals or solutions intended to act as deterrents does not offer great encouragement, though some results seem to warrant further trial in this direction.

e. By means of a preliminary heating, the low or initial stages of oxidation are effected. These sources of contributory heat being removed, the forms of destructive oxidation are without the essential of a high starting temperature and are therefore inoperative. Whether such preliminary treatment is within the realm of practical or industrial possibility could not, of course, be determined within the scope of these experiments.

f. The submerging of coal, it is very evident, will eliminate all of the elements which contribute toward the initial temperatures. As to its industrial practicability, like the conditions under *e* above, it can best be determined by actual experience.

g. Other processes may be suggested by the formulation of the principles involved. Such, for example, would be the distribution throughout the coal of cooling pipes through which a liquid would circulate having a lower temperature than the mass. This would serve to carry away any accumulation of heat and confine the oxidation to the lower stages only. On the contrary the proposition sometimes made to provide circulating passages for the transmission of air currents is of questionable value, since it may result in the contribution of more heat by the added accessibility of oxygen than will be carried away by the movement of the air.

APPENDIX

APPENDIX

Historical Review with Summary of Opinions

The literature upon the spontaneous combustion of coal is widely scattered and difficult of access to a majority of those most directly interested in the topic. In this series of investigations, a considerable amount of time has been spent in assembling these discussions and making synopses of the same. In order that the results of this phase of the work may be made accessible, a review of the literature upon spontaneous combustion is presented in this Appendix.

Grundmann's[1] work, published in 1862, was probably the first serious attempt to study the weathering losses of coal. He found that while the coals lost gaseous constituents, they gained in hydroscopic moisture and so the specific gravity of the coal remained constant. He states that large pieces weather less than fine coal, and that rain and increased temperature accelerate the weathering. Using the percentage of ash as a basis to calculate the change in weight that took place during storage, he found that a pile of 300 tons lost 58 per cent in weight in nine months.

Reder[2] in 1866 was among the first to follow up Grundmann's work. He found that storing coal for a year caused a deterioration in the heating value; but, contrary to Grundmann's results, he found no appreciable loss in weight.

In 1865, Varrentrapp[3] reviewed Grundmann's work of 1862. Varrentrapp and other later workers could not duplicate the results of Grundmann, and ascribe his errors to poor sampling. Varentrapp found from his experiments in storing coal that the oxidation of fresh coal is very rapid, and within the heap leads to a rise in temperature, which, however, is very far from the ignition point.

He states, however, that temperatures reaching the ignition point and causing combustion have at times been found.

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[1] Carnall Zeitschrift, Vol. X, page 236, 1862.
Zeitschrift fur Berg, Hutten, und Salienwesen im preussischen Staate, Band IX und X.

[2] Oesterr. Zeitschrift fur Berg und Hutten, Vol. XV, 1867.

[3] Dingler's Polytechnic Journal, 1865, Vol. 175, page 168. Vol. 178, page 379.

L. Thompson[1] in 1865 found that dry coal in storage for six months lost $\frac{1}{13}$ of its calorific value; if, however, the coal was moist, the loss was much greater. He divides the weathering of bituminous coals into two classes known as "dry rot" and "wet rot". The latter he considers to be a sort of fermentation in which a part of the hydrogen escapes and some of the carbon is oxidized to carbon dioxide; in this way the coal loses calorific value in two directions.

Fleck[2] in 1865 examined a series of six Saxon coals which had been preserved in a cabinet since 1856. The results of his examination were compared with analyses made nine years previously, when, it is presumed, the coals were in a fresh state. After such an exposure in a dry place, three of the number, it was inferred, showed an important increase in proportion of ashes together with a corresponding decrease of organic matter, while the ashes of the remaining three appeared to have decreased. The explanation of such unlike results was sought by Fleck in the lack of uniformity of the related samples, especially as to the ratio of ashes. An increase of oxygen and of indisposable hydrogen was observed in each case, together with a loss of carbon and of disposable hydrogen. Hence the conclusion that, at ordinary temperatures, bituminous coal sustains a loss in carbon and of disposable hydrogen, and proportionately a loss in calorific value, which is increased in proportion to the addition of combined water.

The most careful of the early experiments made on this subject were those of Dr. Richter[3] from 1868 to 1870. He concluded that the weathering of coal was due to the absorption of oxygen, part of which goes to the oxidation of carbon and of hydrogen in the coal, and part of which is taken into the composition of the coal itself; that if the heap becomes warm, either through this process or through any other cause, the action is accelerated, but then falls off, and becomes so slow that the changes effected within a year become difficult to estimate; that moisture, as such, has no direct influence upon the process apart from the presence of pyrites or from the coal crumbling down more rapidly when wet than when dry and, therefore, more rapidly heating up; that if the temperature does not go beyond certain limits (338° to 374° F.) there is no appreciable loss of weight, but rather, on the whole, a gain through the absorption of oxygen. Also, that it is not necessary to explain the loss in heating value, of coking power, and of gas yield by any theory of new arrangements of atoms, for it is sufficient to look at the absolute loss of carbon and hydrogen and the increase in the proportion of oxygen. At a later date, he concluded that large coal was affected less than small, not because it had less surface, but because small coal was a more active absorbent of oxygen, and, therefore, became more rapidly heated; that air-ways in a heap would have to be very numerous in order to prevent any rise in temperature; and that the heap ought to be so constructed as not to allow air to get from the air-ways into the bulk of the coal.

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[1] London Journal of Arts, June, 1865, page 321.
Dingler's Poly. Journal, 1865, Vol. 178, page 161.

[2] Technik der Steinkolen Deutschlands. 1865, Vol. II, page 221,
Transactions of the American Institute of Mining Engineers, Vol. 8, page 207.

[3] The Gas World, April 13, 1901.
Dingler's Poly. Journal, Vol. 190, page 398; Vol. 195, page 315; Vol. 195, page 449.
Vol. 193, page 54; Vol. 193, page 264.

Haedicke[1] in 1880 assigned to pyrites the leading part in spontaneous ignition, conditioned on allowing the temperature to rise sufficiently.

Professor Fischer[2] of Gottingen, in his work on this subject prior to 1901 concluded that storage depreciation and spontaneous ignition were phenomena of oxidation; the part which is played by iron sulphide was disputed, but the variances which have given rise to the uncertainty were due to the differences between the different sulphides of iron present in coal. He claims that marcasite, for example, is much more weatherable than ordinary pyrite. Actual wetting is much more promotive of oxidation of the iron sulphide than heating in dry or even moist air. Besides this, Fischer finds that many coals contain sulphur in the form of unsaturated organic compounds. He finds that those coals which rapidly absorb bromine are those which are most liable to rapid oxidation and spontaneous ignition; as a practical test, he recommends shaking a gram of the finely powdered coal with 20 c. c. of a half-normal solution of bromine for five minutes. Then, if the smell of bromine has not disappeared the coal may safely be put in storage; if it has, the coal should be used up as soon as possible. The absorption of oxygen by the unsaturated organic compounds referred to is accompanied by a gain in weight and at the same time by a rise in temperature; and the warmer the mass the more rapidly does the oxidation go on, so that the temperature is apt to rise to a dangerous extent. Concurrently with the oxidation of these products, is the oxidation of another set of organic compounds with evolution of carbon dioxide and water vapor, and this results, not in a gain, but in a loss of weight. Whether the mass as a whole gains or loses weight is, therefore, a question of the composition of the coal, but the loss in weight is in no case great. Covering wet slack coal with other coal is apt to produce spontaneous ignition; the danger here appears to arise from the sulphide of iron rather than from the organic compounds. Fischer regards ventilation of the coal heap with suspicion, not because the idea is in itself a wrong one, but because it is not practicable to ventilate the whole heap efficiently. He claims that the coal should be stored dry and kept dry under cover, and in layers not too deep.

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[1] The Gas World, April 13, 1901.

[2] ibid.

In a paper read before the German Gas Association in 1900, Herr Sohren,[1] Manager at Bonn, stated that it is no longer possible for many reasons to work gasworks with a supply of coal renewed from month to month; and that all questions affecting storage have, therefore, a continually increasing importance. Undoubtedly there is a greater or less depreciation in the quality of coal kept in store, and the causes of this have attracted a good deal of attention; though, on the whole, it is surprising to find to how great an extent the study of the chemistry of coal has been neglected. Questions of this nature assumed importance in connection with the spontaneous ignition of cargoes of coal in ships; in 1874, out of a list of 4485 coal laden ships, no fewer than 60 caught fire.

In a paper read by Professor Vivian B. Lewes[2] at the 31st Session of the Institution of Naval Architects held at the Society of Arts, Adelphi, the author began by referring to the appointment of a Royal Commission in 1875 on the proposition of the Board of Trade and a Committee of Lloyds, to investigate the causes of the spontaneous ignition of coal cargoes, which had entailed serious loss of life and destruction of property. The Commission was assisted by Dr. Percy and Sir Fred Abel.

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[1] The Gas World, April 13, 1901.

[2] The Journal of Gas Lighting, Vol. 55, page 645.
The Journal of the Society of Chemical Industry, Vol. 9, page 483.

From 1875 to 1883 no less than 57 coal laden vessels were known to have been lost, while during the same period 328 were missing from unknown causes, though probably a large proportion of these losses were due to spontaneous combustion. In view of this fact, it was suggested to the author that an inquiry into the causes and possible prevention of this serious evil was greatly needed in the Royal Navy as well as in the merchant service; he therefore undertook it, and laid the results before the members of the Institute.

The author proceeded to point out that, besides the carbon hydrocarbons, coal contains certain mineral substances, as sulphate of lime or gypsum, silica, and alumina, while in nearly all kinds there is to be found disulphide of iron, "brasses" or pyrites. Of these constituents, those that are likely to produce heat and cause spontaneous ignition in newly-won coal are the carbon, hydrocarbons, and brasses, which, when they come in contact with air and moisture, give rise to certain chemical actions. He then described at length the influence of each of these substances in the production of heat. Taking carbon first, he remarked that it is one of those substances which possess to an extraordinary degree the power of attracting and condensing gases upon their surfaces, the power varying with the state of division and density of the particular form of carbon used. In the case of newly-won coals, the least absorptive would, he said, take up one and one-fourth times, and others would absorb three times, their own volume of oxygen. This absorption is very rapid at first, but gradually decreases, and is influenced to a very great extent by temperature. Air-dried coal absorbs oxygen more quickly than wet coal.

Dealing in the next place with the action of the bituminous constituents of coal in causing spontaneous ignition, the author explained that all coal contains a certain percentage of hydrogen, which is in combination with some of the carbon and also with the nitrogen and oxygen, and forms with them the volatile matter in the coal. The amount present in this condition varies very largely, being very small in anthracite and very great in cannel and shale. When the carbon of the coal absorbs oxygen, the compressed gas becomes chemically active and soon commences to combine with the carbon and hydrogen of the bituminous portions, converting them into carbon dioxide and water. This chemical activity increases rapidly with rise of temperature, so that the heat generated by the absorption of the oxygen causes the latter to enter rapidly into chemical combination. Chemical combination of this kind, i. e., oxidation, is always accompanied by evolution of heat; and this further rise of temperature again increases the rapidity of oxidation, so that a steady rise of temperature is set up. This taking place in the center of a heap of small coal, which from the air and other gases enclosed in its interstices is an admirable non-conductor of heat, will often cause such heating of the mass that, if air can percolate slowly into the heap in sufficient quantity to supply the necessary percentage of oxygen for the continuance of the action, the ignition point of the coal would soon be reached. It has been suggested that very bituminous coal (such as cannel, shale, and coals containing schist) is liable to spontaneous ignition from the fact that a rise in temperature would cause heavy oils to exude from them, and by undergoing oxidation, might cause rapid heating. Experiment, however, not only shows that this is not the case, but that the heavy mineral oils have a remarkable influence in retarding heating.

The action of iron disulphide, pyrites, or "brasses," in promoting spontaneous ignition was next discussed. The author said that ever since Berzelius first expressed the opinion that the heat given out by the oxidation of iron disulphide into sulphates of iron might have an important bearing on the heating and ignition of coal, it had been adopted as the popular explanation of that phenomenon; and, although the work of Richter clearly proved that this is not the case, the old explanation was still given. Dr. Percy in 1864 pointed out that oxidation of the coal also probably had something to do with spontaneous combustion, a prediction amply verified by Richter's researches some six years later. This disulphide of iron was found in coal in several different forms, sometimes as a dark powder distributed throughout the mass of the coal, and scarcely to be distinguished from coal itself. In larger quantities, it often occurred as thin golden-looking layers in the cleavage of the coal, while it sometimes occurred as large masses and veins, often from 1 in. to 2 in. in thickness; but inasmuch as these masses of pyrites were very heavy, they rarely found their way into the screened coal for shipment, many hundreds of tons of these brasses being annually picked out from the coal at the pit's mouth and utilized in various manufacturing processes. When the air was dry, the pyrites underwent but little change at ordinary temperatures. In moist air, however, they rapidly oxidized when in a finely-divided condition, the first action being the formation of ferrous sulphate and sulphur dioxide, together with the liberation of sulphur. The relative amounts of the latter were regulated by the temperature and the supply of air, while longer contact with moist air converted the ferrous sulphate into a basic ferric sulphate generally termed "misy". It was during this process of oxidation that the heat supposed to cause the ignition was evolved. But when it was considered that some of the coals most prone to spontaneous combustion contained only 0.8 per cent of iron pyrites, and rarely more than 1.25 per cent, the absurdity of imagining this to be the only cause of ignition became manifest. If 100 pounds of coal were taken, and the whole of the pyrites in it concentrated in one spot and rapidly oxidized to sulphate, the temperature would barely be raised to 100° C. if all loss of heat could be avoided. The author had carefully determined the ignition points of various kinds of coal, and found them to be as follows:—

Cannel	698°F.	= 370°C.
Hartlepool	766°F.	= 408°C.
Lignite	842°F.	= 450°C.
Welsh steam	870½°F.	= 477°C.

Hence, no stretch of imagination could endow the small trace of pyrites scattered through a large mass of coal, and undergoing slow oxidation, with the power of reaching the needful temperature. Richter fully realized this point, and discarded the idea of the pyrites doing anything more than adding its mite to the causes which bring about rise of temperature. In this, however, Lewes thought Richter was mistaken, his own experiments pointing to the fact that they might increase the liability to ignition when present in large quantities, and that they do so by liberating sulphur under certain conditions. A still more important part played by the pyrites, is that as it becomes oxidized to ferrous sulphate it swells in size and so tends to split up the coal into small pieces, and, by exposing a large extent of fresh surface to the air, causes increase of temperature and energetic chemical action.

The author, Lewes, then traced the actions which culminate in ignition. He said that on newly-won coal being brought to the mouth of the pit, it at once began, by virtue of its surface action, to absorb oxygen from the air. Unless piled in unusually large heaps and a good deal broken, it did not, however, as a rule, show signs of heating, as the exposed surface was comparatively small; and the air finding its way freely between the lumps kept down the temperature. The coal was now screened, and the obtrusively large lumps of brasses picked out. It was then put into trucks, and enjoyed the disintegrating processes of joltings and shuntings innumerable, every jar adding to the percentage of small coal present, and causing a corresponding increase in the size of the surface exposed to the air. Arrived at the docks, it had to be transferred from the truck to the ship, which was done by one of the numerous forms of tips, shoots, or spouts employed for the purpose; and it was during this operation that more harm was done than at any other period. The coal first shot into the vessel was, by reason of the distance which it had to fall, broken down into small lumps, and, having to bear the impact of the succeeding load falling upon it from a height, rapidly became powdered into slack; while the succeeding loads, falling in on the cone so formed, became more or less broken down so that by the time the cargo was all taken in, a dense mass of small coal was to be found under the hatchway. It was invariably at this point that heating took place, as the large surface exposed fresh to the air by the breaking down of the coal caused rapid absorption of oxygen, and consequent rise of temperature. This set up chemical combination between the oxygen absorbed by the coal, and the hydrocarbons and coal "brasses". The combination of the "brasses" with oxygen caused the swelling of the oxidized mass and the splitting up of the coal. Fresh surfaces were exposed, and more absorption of oxygen took place, the ignition point of the sulphur vapor and sulphur compounds distilled out of the pyrites was reached, and rapidly raised the temperature to the ignition point of the coal. It was only in cases where large quantities of dense coal brasses were present, however, that this action could occur. On examining the evidence to be obtained as to the conditions under which spontaneous ignition of coal ships usually takes place, Lewes found that the liability to such accidents increases with

(1) The tonnage of the cargoes,
(2) The ports to which shipments are made,
(3) The kind of coal of which the cargo consists,
(4) The size of the coal,
(5) The shipping of coal rich in pyrites while wet,
(6) The ventilation of the cargo,
(7) The rise in temperature in steam colliers due to the introduction of triple-expansion engines and high pressure boilers.

Having discussed the chemical and physical conditions which lead to the spontaneous ignition of coal, the author proceeded to formulate precautions tending to prevent such disasters. These had reference to the choice of coal for shipment to distant ports, and to the precautions to be taken during shipment and when the coal is on board. He advised that the coal should be as large as possible, free from dust, and have as little "smalls" as practicable. It should be as free from pyrites as possible, in order to prevent disintegration after shipment; and it should contain when air-dried not more than three per cent of moisture. No coal should, he said, be shipped to distant ports until at least a month had elapsed after it was brought to the surface of the pit's mouth. Every precaution should be taken to prevent the breaking up of the coal while being taken on board, and on no account should any accumulation of fine coal be allowed under the hatchways. When possible, the coal should be shipped dry, as external wetness, by producing oxidation of the pyrites, caused disintegration. When the coal had all been taken in, it should be battened down and the hatches not opened again until the vessel reached her destination, the only ventilation allowable being a 2-in. pipe just inserted into the crown of each coal compartment, and led 12 ft. up the nearest mast, the top being left open. This would be quite sufficient to allow free egress to any gases evolved by the coals, but would not allow undue access of air. Into the body of the coal cargo itself would be screwed, at regular intervals of about six feet, iron pipes, closed at the bottom and containing electrical alarm thermometers, set at a certain temperature, the attainment of which would be indicated by the ringing of a bell which would not cease until the temperature had again fallen, and then the spot in which the heating had taken place would be indicated by an index-board. The existence of overheating having been reported by the bell and recorded by the index, the author offered suggestions for suppressing it. He advocated the injection of compressed carbonic acid gas, and explained his plan as follows: The nozzle attached to the screw valve on the bottle of condensed gas would have a short metal nose-piece screwed on it, the tube of which would be cast in solid, with an alloy of tin, lead, bismuth and cadmium, which could be so made as to melt at exactly 200° F. (93° C). The valve would then be opened, and the steel bottle buried in the coal during the process of loading. The temperature at which the fusible metal plug would melt is well above the temperature which could be reached by any legitimate cause, and would mean that active heating was going on in the coal. Under these conditions the pressure in the steel cylinder would have reached something like 1700 pounds; and the moment the plug melted, the whole contents of the bottle would be blown out of it into the surrounding coal, producing a large zone of intense cold, and cooling the whole of the surrounding mass to a comparatively low temperature. The action, moreover, would not stop here, as the cold, heavy gas would remain for some time in contact with the coal, diffusion taking place but slowly through the small exit-pipe. When coal has absorbed as much oxygen as it can, it still retains the power of taking in a considerable volume of carbonic acid gas; and when coal has heated and then has been rapidly quenched, the amount of gas so absorbed is very large indeed, and the inert gas so taken up remains in the pores of the coal and prevents any further tendency to heating. Indeed, a coal which has once heated, if only to a slight degree, and has then cooled down, is perfectly harmless and will not heat a second time. It is not by any means necessary to replace the whole of the air in the interstices of the coal with the gas, as a long series of experiments shows that 60 per cent of carbonic acid gas prevents the ignition of the pyrophoric substances. One hundred cu. ft. of gas can be condensed in the liquid state in a steel cylinder 1 ft. long and 3 in. in diameter; and it has been shown that a ton of coal contains air spaces equal to about 12 cu. ft. One of these cylinders would therefore have to be put in for every eight tons of coal, and these would be distributed evenly throughout the cargo, and near the alarm thermometers, which would be set to ring a degree or two below the point at which the fusible plug would melt. The bell ringing in the captain's room would warn him that heating was taking place, and the bell would continue to ring until the cylinder had discharged its contents and had cooled down to a safe degree, so that the whole arrangement would be purely automatic, and yet the officers would know if everything were safe. If the precautions advocated were taken, no danger could arise until the arrival of the ship at her destination, and the commonest precautions would then suffice.

In conclusion, the author remarked that the question of preventing the heating and ignition of stores of coal on land and ready for use in bunkers could not be met so well by the use of the liquid gas; and in these cases it would be found beneficial to dress the coals with a little tar or tar oil, which would close the pores, and to a great extent prevent oxidation. He believed this was advocated by Lachman about 1870. Crude petroleum in small quantities would also be found valuable for this purpose, for it has no tendency to oxidize itself, and lowers the tendency in other bodies, besides coating them and so preventing access of oxygen.

In a later paper, Professor Lewes[1] of the Royal Naval College says that, in the spontaneous ignition of coal stored in bulk, the oxidation of the pyrites present plays only a very subsidiary part, the chief factor being the surface condensation of the oxygen in the pores of the coal and the action of the condensed gas in effecting the oxidation of the hydrocarbons present in the coal. While sufficient ventilation to prevent any considerable increase in temperature within the mass is effective in preventing ignition, it is practically impossible to maintain this condition in large coal stores or in a cargo on board ship, where usually only enough air enters to lead to dangerous heating. The recent suggestion to wet thoroughly the whole mass of coal is impracticable, owing to the great increase in weight brought about if sufficient water is added so as to be effective; too small a quantity of water only accentuates the danger.

A. O. Doane[2] in 1904 stated that the amount of moisture present in a bituminous fuel after drying in the air is a measure of the risk of spontaneous ignition when the fuel is stored; bituminous coals containing over 4.75 per cent of moisture are dangerous. Coal bins should be of iron or steel, protected by concrete, and should be roofed over. Free air passages should be provided around the walls and beneath the bins so as to keep them cool, and the depth of coal stored should not be over 12 ft. The customary method of providing air passages in the body of the fuel is useless, since it tends merely to accelerate oxidation and does not produce a sufficient current of air to keep the temperature down. Cracks or joints in the walls of the fuel bin increase the risk of spontaneous ignition for similar reasons.

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[1] The Journal of Gas Lighting, 1906, page 33.
The Journal of the Society of Chemical Industry, Vol.25. page 463.

[2] Engineering News, Vol. 52, page 141.
The Journal of the Society of Chemical Industry, Vol. 23, page 1203.

Durand[1] has explained the spontaneous ignition of coal as being due to the presence of pyrites, which on oxidation under suitable conditions inflames, and then sets fire to the coal in which it is embedded.

According to Fayol's experiments[2], however, the real cause of spontaneous combustion is the oxidation of the coal itself and not that of the pyrites. The absorption of oxygen by coal takes place more or less readily, depending upon the initial temperature and upon the coal being more or less finely divided. Lignite in the state of fine dust takes fire at 150°, gas coal at 200°, coke at 250° and anthracite at 300° or above. On heating a mixture of finely powdered coal and pyrites up to 200° for four days, the coal took up 6 per cent of oxygen, while the pyrites absorbed only 3.5 per cent. Hence coal absorbs oxygen much more energetically than pyrite does, a fact which was confirmed by the following experiment. 900 gr. of powdered coal and 3350 gr. of powdered pyrites were placed in tin cans and put in a drying chamber. Up to 135° both behaved similarly, but from there on the temperature of the pyrites remained almost stationary while that of the coal quickly rose, ignition taking place a few hours afterwards. Two other samples of coal and pyrites were put in a chamber at 200°. The temperature of the coal quickly increased. After 40 minutes, it reached 200°, and the coal took fire, while the pyrites had at the same time been raised only to 150°. The ignition of the coal was not at all hastened by an admixture of pyrites.

Fayol, as a result of some of his other experiments, stated that "The influence of wet weather on heaps of coal has not been sufficiently marked to be observable." On the other hand, much evidence has been given which is absolutely opposed to the above statement. In a letter to the English Commission in 1876,

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[1] The Journal of the Society of Chemical Industry, Vol. 2, page 325.

[2] Bulletin de la Societe de l' Industrie Minerale, Second Series, Volume 8, part 3, 1879

Mr. Poole[1], Inspector of Mines, Nova Scotia, makes the following remark: "Heat has been observed in piles of slack coal that have been accumulated during the summer for the use of engines during the winter, when the season has been showery, but not when it has been dry." Much similar evidence was offered the English Commission; for, out of the 26 answers to questions as to the effect of moisture, every reply was to the effect that moisture was a source of danger. Similar evidence was given at the inquiry held by the New South Wales Commission, although, on cross examination, it was brought out that this view was more a matter of impression than of definite knowledge.

Fayol[2] also found that the coal of Commentry never took fire by exposure when the heaps were less than two meters deep, no matter what the lateral dimensions of the heaps might be. He also found that a mixture of dust and fragments was the most dangerous.

Some valuable evidence on the subject of the size of the storage heap was given to the New South Wales Commission by Mr. Bush[3], the engineer of the Australian Gaslight Company. It appears the Australian Gaslight Company has two coal stores, one at Kent St., and the other at Mortlake. These stores are kept more or less full for gas making. The Kent St. store is filled with coal to a depth of 14 feet, the Mortlake store to a depth of 20 feet. The Mortlake store requires great care to prevent the coal from firing, whereas no case of firing from spontaneous combustion has occurred at Kent St. All other circumstances are, so far as known, exactly the same at both stores. The opinion of Mr. Bush is that the difference in the behavior of the coal in the two stores is to be attributed to the difference in depth of the coal.

"It was formerly supposed[4] that the oxidation of pyrites (a common impurity of coal) is the initial cause of spontaneous heating. This, however, has been disproved in many tests by direct experiment, and it also appears that there is no direct relation between the pyrite content of coal and its liability to spontaneous combustion. On the other hand, if coal is wet, it has been shown that the pyrites tends to oxidize, and in so doing may help to break up the coal and thus render it more liable to spontaneous combustion by increasing the surface. We are of the opinion, however, that the cases of spontaneous combustion of Newcastle coal are not in any way traceable to this action, since we have not been able to find that the cargoes which have fired have been unusually wet, or that the sulphur content was unusually high; in fact, the average sulphur content is only about 0.5 per cent.

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[1] Threlfall, On the Spontaneous Heating of Coal, Jour. of the Soc. of Chem. Ind., Vol. 28, p. 763, 1909.

[2] For an excellent review of Fayol's monumental work on the coals of Commentry, see 1.

[3] Report of the First New South Wales Commission.

[4] From the Introduction to The Report of the First New South Wales Commission, inquiring into the causes of the firing of coal cargoes, etc.

"It still must be regarded as an open question, however, whether the heating of Newcastle coal is in any way dependent on the amount of moisture which it contains. On the other hand, we have the very definite experimental result of Fayol that moisture has no influence whatever on the liability to spontaneous combustion of the coal of Commentry, and yet we see that the disintegrating action of oxidizing pyrite may have an indirect effect.

"Most of the witnesses we examined were of the opinion that wet coal was more likely to fire; and some important evidence was given us by Mr. A. Ross, manager of the Wallsend Mine (Ans. 1379), and also by Mr. Reed, screen overseer, in charge of the hoppers in which the Newcastle-Wallsend Coal Company store their small coal. These witnesses stated that the temperature of the coal in the Wallsend hopper increased within a few days after a shower of rain. On visiting the hopper and digging into the coal to a depth of two or three feet, we obtained samples of coal, some hot and moist, some cool and dry. The place from which the hot sample was obtained was distant only a few feet from the place where the cool sample was taken. Chemical examination disclosed no appreciable difference between the two samples. It occurred to us that possibly the hot coal had been heated by distillation of steam from the coal below, which coal was spontaneously heated, and this we are inclined to think was really the case, for the seat of spontaneous combustion is never within three feet of the surface of a heap of coal. On drawing Mr. Reed's attention to the possibility of this explanation, he appeared inclined to agree with us (Q. 3426-8). We consider it not unlikely that the heating up of otherwise unheated coal by the distillation (and condensation) of steam may have given rise to the idea that moisture is favorable to spontaneous heating.

"Of course, if coal is red hot and small quantities of water are poured upon it, the resulting steam is decomposed by the red hot coal, and the carbon monoxide and hydrogen thus liberated burn with flaming. This fact, also, we are inclined to think may have tended to give rise to the impression that moisture assists the spontaneous combustion of coal.

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"It is, perhaps, obvious from what has been said on the subject of the absorption of oxygen by coal, that a very important condition is the initial temperature of the coal. From two cases which came under our notice, we are inclined to think that the masters of ships are not sufficiently alive to the importance of keeping the coal away from the hot surfaces, especially when the surfaces are themselves far below the ignition point of coal. A donkey-engine and boiler, for instance, may be separated from the hold by a cement floor laid on the deck planking, and so far as we could ascertain there seemed to be an impression that the heat which could be transmitted through such a shield could have no ill effect on the coal. The fact is, however, that the rate of absorption of oxygen increases so greatly with rise of temperature that the moderate warming of the coal by a steam pipe or boiler may enormously shorten the time necessary for spontaneous combustion to set in, or may render spontaneous combustion possible in cases where it would otherwise be impossible."

These remarks apply with great force to the practice of loading coal in very hot weather. The coal lying in trucks on the dyke and exposed to the sun is loaded at a temperature which it might take months to reach if it had to generate the necessary heat by absorption of oxygen. This reasonable conclusion is supported by the fact that three very large ships were loaded together during the hot weather of January, 1896, and all of them were the victims of spontaneous combustion.

The acceleration of the rise of temperature consequent on a large initial temperature is also well illustrated by the cases of the "Knight of St. Michael", the "Morna", and the "Invernay", all of which were loaded during extremely hot weather, and all of whose cargoes became dangerously heated within a short time of loading.

The United States Admiralty[1] has made experiments and gives valuable directions for preventing the spontaneous combustion of coal. Anthracite is excluded from the inquiry since only bituminous coals are liable to catch fire. The ignition of coals may be induced by condensation and absorption of the oxygen of the air by the coal, whereby the temperature is raised so high that chemical combination between the hydrogen and oxygen can take place. This easily happens if the coal be very pure and brittle, if the outside temperature also be high, and the necessary ventilation be wanting. Another cause of ignition is the action of moisture on the sulphur of many pyritic coals, not so much from the heat of the chemical reaction as from the circumstance that the coal is split and broken up, and so fitted for the absorption of oxygen.

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[1] Oesterr. Zeits. Fur Berg und Hutten, Vol. 47, page 78.
The Journal of the Society of Chem. Industry, Vol. 18, page 568.

The arrangements for preventing ignition on board ship are not taken up, but it said that on land it is mostly the pyritic coals that take fire. Care should be taken that the coal is stored on iron floors, and covered, the height of the heap not to exceed two to two and one-half meters. For sea voyages, the coal should not be loaded earlier than one month after it has been mined.

Mr. Stelkins[1], in his report before the International Navigation Congress in 1902, stated that the tendency towards spontaneous ignition of coal increases with the height to which the coal is piled. Stacks higher than 15 ft. should not be made. Rain during and after stacking and compression caused by dumping coal from a great height on the stack, all add to the danger of ignition.

Mr. F. M. Griswold[2] of the Home Insurance Company, in 1904, states that spontaneous ignition is more marked in free burning or so-called "high steaming coals" including "gas coals". These coals usually contain a large amount of volatile matter and small amounts of oxygen. The tendency towards spontaneous ignition increases when sulphur or lignites are found in the coal and especially when pyrite is present. Slack, mine run, and dirty coal are dangerous because of the fine particles present, the latter gradually sifting to the bottom and being compressed.

According to Mr. Griswold, a satisfactory explanation of spontaneous ignition and combustion of bituminous coal has not as yet been made. The best authorities say it is due to chemical changes in the substance of the coal resulting from the absorptive powers of carbon, the latter increasing with the rise in temperature. Rise in temperature may be due to the chemical action caused by slow oxidation or to the mechanical force of pressure; both of these conditions may be stimulated by moisture and the presence of pyrites. Some claim that over 2½ per cent of sulphur in the form of pyrite is dangerous. Various tests have been proposed to determine the liability of a coal to heat, such as the gain in weight of the coal at 250° F. and the absorption of bromine, but these tests are not valuable, as it is difficult to tell how much oxygen the coal has already absorbed. He recommends that no wood be used in the construction of bins, that all ironwork be covered with concrete, that no steam pipes or flues be near the bins, that a good circulation of air be about the sides and under the bins, and that the coal should not be piled to a depth greater than 12 ft. He also recommends that the bins be roofed, and that they contain pipes in which thermostats should be placed, and when the latter register 140° F., something should be done to stop the rise in temperature.

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[1] American Society of Naval Engineers, February, 1901

[2] Engineering News, November 10, 1904, page 409.

A. E. Dixon,[1] in 1906, stated that spontaneous ignition occurs with friable bituminous coal, and particularly with those grades containing brasses or iron pyrites; when the coal is damp, the trouble is increased. The cause is probably due to the absorption of oxygen by the carbonaceous material, just as is the case with oily cotton waste.

An article describing the coal storage department of the works of the Lackawanna Steel Company[2] says "Derricks are used to pile the coal and they are able to pile it to a height of 60 feet; but to avoid spontaneous combustion, it was deemed advisable to restrict the height of the piles to 20 or 30 feet."

Mr. Peter Bullock[3] cites several cases of coal piles catching on fire, seemingly due to spontaneous combustion. In all, about ten or twelve cases were cited; about half of these cases he believes to be due to heating from steam pipes which were near by, for the others he gives no explanations.

Groves and Thorp[4] state that gases occluded in the crevices or cavities of the coal escape during mining and continue to do so after storage. The inflammable nature of these gases makes them a source of great danger, for it is believed that they are the causes of many of the disastrous explosions on board vessels carrying coal as a cargo.

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[1] Engineering News, November 10, 1904, page 409.

[2] Engineering Record, July 4, 1903.

[3] Power, 1908, page 675.

[4] Groves and Thorp, Chemical Technology, page 82.

Parr and Barker[1], working on the gases occluded in Illinois coal, found that two active processes are set up immediately upon liberation of the coal from the vein. The first is an exudation of hydrocarbons, consisting mainly of marsh gas (CH_4), and the second is an absorption of oxygen. They found that after a period of two months practically all of the marsh gas had been liberated and, although the avidity of the fresh coal for oxygen was very pronounced, after a period of two months, active absorption of oxygen still took place.

The work of R. T. Chamberlin[2] on explosive mine gases and dusts confirms the above work of Parr and Barker. Working on the gases occluded in the coals of the Naomi, Monangah and Darr mines of Pennsylvania and West Virginia, the author found that after the extraneous nitrogen had been removed, methane was by far the most important gas which escaped from the bottled coal. In some tests it ran as high as 98 per cent of all the gas coming from the coal; more commonly, however, it constituted from 80 to 95 per cent of the gas liberated. The finely crushed coals gave out methane at a very rapid rate, practically all of it in a period of 8 or 10 weeks, whereas the small lump coal gave out the methane at a slow uniform rate, although after a period of 26 weeks the total volume of methane given off almost equaled that given off by the fine coal.

Working on the comparative inflammability of coal dusts from the three mines mentioned above, within a few days after the unusually violent and fatal explosions which swept all three, the author points out some valuable facts concerning the absorption of oxygen by coal. He found that comparatively little oxygen can be extracted from coal, although very large volumes of oxygen are rapidly and steadily absorbed by the coal. The experiments with coal dust indicate that, with exposure to the action of the air, there is a development of the oxides of carbon and sulphur within this dust, or of compounds which give off these gases at moderate temperatures. Coal bottled in air for a few weeks gives off a much higher proportion of carbon dioxide than if placed in a vacuum; but it does not give off as carbon dioxide, within a short time at any rate, more than a small percentage of the oxygen absorbed from the air in the bottle. Air bottled with Illinois (Cardiff mine) coal for two weeks contained at the end of that time only 1.05 per cent of oxygen and 1.59 per cent of carbon dioxide, together with 0.62 per cent methane and 96.74 per cent of nitrogen. Thus only a small proportion of the oxygen which goes into coal comes out again as carbon dioxide. The formation of water by the oxidation of a part of the hydrogen in the coal is a natural explanation for the apparent disappearance of some of this oxygen. It may also be that some of the organic compounds have been only partly saturated and hence the oxygen absorbed is not given off at once as carbon dioxide, but comes off later when the oxidation has progressed further.

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[1] University of Illinois, Engineering Experiment Station, Bulletin No. 32, 1909.

[2] Bulletin 383, U. S. Geol. Sur. "Explosive Mine Gases and Dusts", 1909.

Dennstedt and Bünz in 1908[1] exaggerated the conditions of spontaneous combustion by passing oxygen through a sample of coal at 135° or 150°C. The coals tested by them are divided into four classes:—

1. Coals whose temperature never rises above that of bath.
2. Coals that rise only slightly above the bath temperature.
3. Coals that rise fairly high, but will not take fire unless the oxygen supply is carefully increased with the rise in temperature.
4. Coals that take fire easily, usually in about two hours.

Six typical coals were selected to determine what chemical variations accompanied the above classes. They found that coals that have been thoroughly wet kindle more rapidly than if they have been kept dry. Quoting their conclusions, we find: "Self-ignition increases in a ratio corresponding to the amount of moisture in air-dry coal; mechanically combined moisture is not meant, for the coals used gave the impression of being perfectly dry; the moisture seems to be water of constitution.

Surface absorption has the same degree of importance as the above water of constitution. The question certainly is not one of hydroscopicity, or of the hydroscopic inorganic salts present, for water-soluble mineral salts are found in very small quantities in all coals, so small that they do not even increase the surface absorption.

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[1] Zeitschrift fur ang. Chemie, 1908, Vol. 21, p. 1825-35.

Moisture and its reabsorption are allied to, or controlled to a certain extent by, the organic substances and their composition. It may also be noticed here that the humic acids formed in the coals are exceedingly hydroscopic. But these cannot cause the surface absorption in the original coals, because no completely formed humic acids are present; therefore the increased surface absorption of the oxidized coals is undoubtedly due to the humic acids. The increasing Maumene number (with increasing self-ignition) is also in accordance with the idea of water of constitution, and here it is also seen that the organic substances have an influence, for the Maumene number increases in the same ratio, even in those coals that are dried in a current of carbon dioxide. It is very remarkable that these coals, dried in this way, should cause a rise in temperature when they are stirred in cold water (this property increases as self-ignition increases). The Maumene number can, therefore, well serve as a standard which would decide a coal's power of self-ignition.

Neither amount nor kind of mineral substance nor pyrite found in coal has any effect on the self-ignition; this is seen without a doubt from a consideration of the analytical data. The pyrite content is very small, and besides the pyritic coals are not the easiest to self-ignite. One could also think of certain catalytic actions; to this effect there were made numerous observations upon coals which had caused fires, and they had only a very small amount of pyrite that occurred in a fine condition. This pyrite was found in a slaty portion of the coal and upon fresh cleavage fractures in the form of a fine sulphur-colored film. But the fact that just such coals, which are very easily self-ignitible, such as Scotch coal No. 6, contained a minimum quantity of pyrite, carries one away from the above idea. The same might be thought of the hydrochloric acid soluble iron in the original coal,—that this might be due to a catalytic action, but here also the amount is small and does not grow with the degree of self-ignition so that it was not thought necessary to insert the analytical data in the tables. One could rather speak of the water-soluble iron in the oxidized coal as due to this cause; sometimes in coals that have been stored for a long time and perhaps have become wet too, an oxidation of pyritic iron in the form of basic sulphate is found, but we did not find any increased self-ignition in them."

From the above, it seems without a doubt that the organic substances control the self ignition of coal, and it depends not so much on the amount but rather upon the kind and composition. This follows directly from the ultimate analysis; of course, the amount of organic combined sulphur and nitrogen has no effect. For it is seen that neither is found in any great amount in coals that are easily inflammable over coals not easily so. With the sulphur one could think of the formation of easily inflammable compounds, for example, carbon bisulphide. During the oxidation process, carbon bisulphide was expected, but no trace was found. Very conspicuous in the elemental composition is the proportionately small amount of hydrogen in the more inflammable coals, and the particularly larger amount of oxygen which is especially noticeable in the small amount of available hydrogen.

Quoting further from these writers:—"If the self-warming and ignition are caused by this oxidation, which we believe has been shown, then at first glance it seems a contradiction that those coals already so rich in oxygen are the most easily oxidized. But when one thinks that all coals are finally tending toward a similar or equal character or composition, then one can easily picture that a transition period of marked inflammability exists, which the easily inflammable coals have already reached. This is in accordance with the remarkable properties of the coals in Class II, which with preparatory treatment at 135°C. with oxygen, become more easily inflammable. This point seemed to be of sufficient weight to cause certain quantitative experiments to be made so as to prove it. With coal No. II (Germania) a marked change takes place by treating with oxygen at 135°C. This change consists of an addition in weight and a considerable loss of carbon dioxide and water, and this, we think, proves our assertion. Of course it is not necessary in order to change to an inflammable coal that the above must take place throughout the entire coal. It is sufficient if it happens in certain localities or perhaps only at the surface of small coal particles. That the addition in weight which takes place in oxidation, caused by the taking up of oxygen, is not substantially less in the less inflammable coals, with the exception of the altogether uninflammable coal marked Nixon Navigation, rests clearly on similar reasons, (the same is found under Table 7), from the ultimate analysis of the oxidized coal showing the addition of oxygen and the loss of carbon and hydrogen. Altogether out of place in this respect is the uninflammable coal No. 1, Nixon Navigation, which oxidizes very slowly.

"The end product of the oxidation is clearly seen to be the humic acids, and from the humic number is found without possibility of contradiction how far the easily inflammable and oxidizable coals are above the others. Less easy to account for is the fluctuating value or amount of pyridin extract, especially when one sees the content of the original and oxidized coals; but one thing is certain, that in the majority of cases the extract grows with the degree of self-ignition and is increased by oxidation. The one exception is coal No. II, which is perhaps ascribable to imperfect methods.

"Our researches show that the organic parts of the coal play two different roles which have little to do with each other. That portion soluble in organic solvents seems of similar character and composition and perhaps of similar origin as the soluble portion of Braunkohle, for example, the so-called Montanwachs, only the coal extract contains more oxygen and is therefore probably of similar origin but changed by oxidation.

"That portion of the coal insoluble in organic solvents we look upon as the real coal substance probably formed from cellulose in the original wood; and it is that substance which on further oxidation yields the humic acids and which, although not altogether still in the main part, determines the self-ignition of the coal. It contains also the unsaturated compounds upon which the iodine addition rests, which in the iodine number express themselves quantitatively, and they run parallel with the capacity for oxidation; the remarkable fluctuation of the iodine number in the original and oxidized coals we leave for the present purposely untouched.

"But, since the iodine number is so easy to determine, one has in the main a practicable means next after the Maumene number for determining the degree of danger from fire of the coal."

Summarizing their work it is seen that spontaneous combustibility increases with the following:—

1. Moisture at 105°.
2. Brittleness.
3. Iodine number.

4. Maumene number.
5. Humus number.

Graefe[1] noted that naturally weathered coal contains more ash, is of a lower calorific value, and on distillation gives less tar but has a higher paraffin content than the fresh coal.

Erdmann and Stolzenberg[2] found the work of Graefe to be in accord with the assumption that it is the unsaturated bodies, viz., the humus, that undergo slow oxidation. That the humus is the unsaturated body is shown by the fact that it absorbs large amounts of bromine without the evolution of hydrobromic acid, and also that it has a vigorous reaction with ozone. The humus can be extracted from the coal with alkali and separates on acidifying. A current of oxygen containing 2 per cent of ozone passed over humus in a U-tube at the rate of 500 c. c. per minute causing combustion in 23 minutes. Briquet coals coarsely powdered and moistened took fire in about 70 minutes; while dry, the temperature did not rise over 48°C. These experiments lead the authors to the conclusion that the self-ignition of small coal is due to the action of ozone.

Dry pyrite showed no increase of temperature; moist, only a 12° rise. A mixture of humus and 10 per cent of powdered marcasite (crystalline pyrite) took longer to ignite than pure humus; consequently, pyrite is not the cause of spontaneous combustion in coals.

The self-ignition of coal is probably not determined by the ozone content of the air but rather by the production of ozone, which is found by the evaporation of moisture from the surface of the moist coal. In agreement with the above statement is the fact that fires in coal heaps occur more frequently on warm, sunny days after a rain where the surface evaporation is especially great. The ozone found under these conditions immediately begins to react with, and is absorbed by, the humus substances which break up by its action in the presence of water into carbon dioxide and saturated cleavage products such as humic acid. The heat produced by this reaction accumulates when sufficiently insulated, and the rising temperature also causes the more inactive atmospheric oxygen to react, so that under favorable conditions the temperature will rise to the ignition point.

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[1] Braunkohle, Vol. 6, 713.

[2] Braunkohle, Vol. 7, 69
Chemisches Centralblatt, Vol. 79, p. 456, Aug. 5, 1908.

The reaction of coals with ozone as first described is a measure of their tendency to spontaneous combustion.

Moist cellulose (filter paper) showed no rise in temperature in 2 per cent ozone, wheat bran rose only 4.5°, while cotton waste soaked in linseed oil ignited very quickly.

O. Boudouard[1], 1909, in his work on the oxidation of coals and the products resulting therefrom found that in contact with the air at 100°C. coal readily undergoes oxidation; the increase in weight, through absorption of oxygen, in some cases being as high as 10 per cent. After oxidation in this way, coal is found to contain humic acid and to have lost its power of coking. The author then extracted the humic acid by means of potassium hydroxide solution from seven varieties of coal, both before and after artificial oxidation. The results of the fourteen analyses show that the chemical constituents of the humic substances thus obtained correspond with one or more of the following formulas:—

1. $C_{18} H_{14} O_6$ (Bertholet and Andre)
2. $C_{18} H_{18} O_9$ (Malaguti)
3. $C_{18} H_{14} O_{11}$
4. $C_{18} H_{14} O_{11}$

and that the effect of oxidizing the coal is to diminish the carbon and increase the hydrogen and oxygen content of the humic substance yielded by the coal. Concentrated nitric acid causes more complete oxidation and increases the yield of humic acid.

In an attempt to account for the coking power of coal, several samples were submitted to the effect of various organic solvents. Beyond the extraction of a small amount of resinous matter, these solvents had little if any effect. Concentrated hydrochloric, sulphuric and nitric acids, also 25 per cent potassium hydroxide solution, and finally Schweitzer's reagent, were tried. Concentrated hydrochloric acid had no effect, concentrated sulphuric and nitric acids destroyed the coking power, the 25 per cent potassium hydroxide solution and Schweitzer's reagent reduced the coking power considerably. The successive action of the potassium hydroxide solution, hydrochloric acid and Schweitzer's reagent caused the total loss of coking power; the solubility of the cellulose-like substances in the Schweitzer's reagent is the explanation given for this result.

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[1] Bulletin de la Societe Chimique, Vol. 5, 365; 372; 377; 380.
Compte rend. 147, 986; 148, 284; 348.

The humic acids found in the oxidized non-coking coals are probably the carbohydrates of the original coal in a condensed and polymerised condition. (Note: The polyatomic alcohols, sugars, etc., furnish humic derivatives by condensation and dehydration under the influence of or in the presence of heat or alkalis and acids. These humic substances thus artificially prepared are found to be very similar in composition to those extracted from peats and lignites. These facts tend to substantiate Fremy's theory[1] of the formation of peats through the fermentation of vegetable matter and the subsequent formation of coal through the agencies of heat and pressure). The fact that anthracite has not the power to make coke is easily explained; this class of coals represents the furthest progress in the metamorphosis of the plant material which no longer contains cellulose. In fact the natural or oxidized anthracites are free from humic acid. Special attention must be given to the fact that even a minute amount of humic acid is sufficient instantly to cause the loss of coking power.

Dr. Haberman[2] found that coal stored for a long time became unfit for the manufacture of gas, and that the coals lost in gasifying and coking value and also in heating power. He claims that the spontaneous combustion of coal is due to the absorption of oxygen by the coal substance. He gives the result of a series of experiments on spontaneous ignition in which he used 200 kilograms and then heated these samples in a fire brick retort at 50°C. The coal was supplied with air at a temperature of 24°–26°C. and practically ignited in 36–39 hours. He found that coals that oxidized the most and gave the greatest rise in temperature absorbed the largest quantities of bromine.

Parr and Francis[3], working upon the modification of Illinois coals by a low temperature distillation, found that active oxidation was effected at an unexpectedly low temperature. They found that a considerable quantity of carbon dioxide was given off by the coal on distillation in an atmosphere of nitrogen and steam, and a much larger amount was given off when an atmosphere of oxygen was used. Under the latter condition an occasional rise of the temperature in the retort was noted, seemingly independent of the external source of heat. This fact led to a series of experiments wherein careful temperature observations were made and in which the outgoing gas could be tested for carbon dioxide. Using an atmosphere of pure oxygen, they found carbon dioxide evolved at about 120°C., the kind of coal seemingly being immaterial, for Illinois coal, Pittsburg gas coal, and anthracite were used. Ignition temperatures ranged from 160° to 300°C. Using air as an atmosphere, the initial appearance of carbon dioxide was about 135°, instead of 120° with pure oxygen. This result is what would be expected, for the dilution of oxygen in the air by nitrogen would retard or lessen the activity of oxygen. At 280° a rapid rise in the oxidation temperature took place, notwithstanding the cessation of the external heat. This fact was observed on a sample of Illinois bituminous powdered coal in an atmosphere of air. Seemingly, therefore, we have here an illustration of a type of combustion which, while still below the ignition point, is still self-supporting and would be continuous, depending upon the oxygen supply.

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[1] Comp. Rend. 88, p. 1048, (1879).

[2] Schillings' Jour. fur Gasbeleuchtung u. Wasserversorgung Vol. 49, p. 419.

[3] University of Illinois, Engineering Experiment Station, Bulletin 24. (1908)

White[1], in studying the oxygenation and weathering of coal, notes that, in general, the lower classes of coal take up oxygen on exposure to the air. This, together with some immediate loss of compressed volatile matter (cf. work of Parr and Barker) appears to mark the first phase of weathering. Later, and on prolonged exposure, there seems to be a considerable loss of carbon and hydrogen also, especially in the humic (ordinary) coals.

The weathering of the lower grades of coal, especially bituminous, lignites and peats, is marked by the accession of oxygen which is taken into combustion. This increase of the oxygen contents, which seems to indicate lack of equilibrium in the hydrocarbon compounds of the normal coal, readily permits a calorific deficiency which, on account of the high calorific value of oxygen, is often serious.

SUMMARY OF OPINIONS

Reviewing the literature given in the preceding chapter, it may be seen that opinions differ as to the real causes of spontaneous combustion. The leading factors may, however, be summed up as being the following:

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[1] U. S. Geol. Sur., Bulletin 382, "The Effect of Oxygen in Coal."

1. The kind of coal, in regard to its volatile matter.
2. The purity of the coal.
3. The presence of pyrite or other sulphur compounds.
4. The temperature of the coal.
5. The size of the coal.
6. The presence of occluded gases in the coal.
7. The presence of moisture.
8. The accessibility of oxygen.
9. Pressure on the coal.

1. *Kind of Coal.*—From the ignition temperatures given by Fayol, it may be seen that only those coals (such as lignites, bituminous and semi-bituminous) containing large amounts of volatile matter, are liable to ignite spontaneously, and that anthracite with its very low percentage of volatile matter is practically entirely excluded. The results of the work of O. Boudouard, on the coking power of coals, also substantiates this view, for in his work he found that those coals richest in volatile matter (carbohydrates, cellulose, etc.,) were most liable to spontaneous combustion.

2. *Purity of Coal.*—The work of our own government seems to indicate that coals of exceptional purity are more apt to heat up than coals containing large amounts of extraneous matter. This is probably due to the fact that very pure coals are able to condense and absorb the oxygen of the air much faster than other coals and so cause an increase in temperature, which finally results in the chemical combination of the oxygen and hydrogen occluded in the coal. This view is confirmed by the later work of Dennstedt and Bünz, who found that those coals causing spontaneous combustion or those coals which oxidized and increased in temperature most rapidly were remarkably free from mineral matter and pyrite.

3. *Presence of Pyrite.*—As to what part sulphur compounds, especially pyrite, play in the spontaneous ignition of coal, opinions differ greatly. Some believe pyrite to be the leading factor, while others believe it plays no part at all, or, if so, ascribe to it a position of minor importance and believe its action to be merely a subsidiary one. The oxidizing action of the air upon pyrites is, however, admitted, and the notion seems to be fairly general and

well established that pyritic oxidation tends to raise the temperature of the coal. On the other hand, it is seen from the work of Fayol, Dennstedt and Bünz, Threlfall and others that coals containing pyrite in a quantity too insignificant to be noticed are very apt to ignite spontaneously. The Newcastle coal of New South Wales is also a very good example of this class of coals.

Others, however, believe that the only influence of the pyrite is a mechanical one, in which the oxidation of the thin films of pyrite in the coal serves merely to break up the coal.

4. *Temperature of the Coal.*—Most of the authors agree that the temperature of the coal undoubtedly is one of the main factors in the whole subject of spontaneous combustion, for cases of spontaneous combustion have occurred time and again where probably they never would have occurred if there had not been an initial heating in some way or other. The New South Wales Commission thinks that the initial temperature of the coal at the time of storage or loading is one of the great factors in the subject of spontaneous combustion, the true danger of which has not heretofore been fully appreciated. Sources of heat seemingly insignificant are frequently the cause of bringing the temperature of the coal up to the danger point and so causing coals to ignite which, under carefully regulated conditions of storage, would not be at all dangerous. Numerous cases are on record where the cause of the spontaneous ignition of large coal stores and loads was finally traced back to initial heating from flues, steam pipes, or direct exposure to the sun. This increased temperature, whether coming from outside sources or from physical or chemical reactions within the coal, tends to accelerate the absorption of oxygen and thereby to raise the temperature of the coal. It also tends to drive out the inflammable gases occluded in the coal, and so greatly to accentuate the danger of spontaneous ignition.

5. *The Size of the Coal.*—That fine coal is a more active absorbent of oxygen and more liable to ignite spontaneously than large coal was shown as far back as 1868 by Richter. Practically all of the later experimenters in this field concede this to be true, for, having a greater surface, the fine particles can absorb much more oxygen than large lumps; and since this rapidity of absorption causes an increase in temperature, which in turn produces favorable conditions for further absorption and for chemical action between the oxygen of the air and the hydrogen of the coal,

the danger of spontaneous combustion is greatly increased.

Throughout the literature, warnings are found cautioning coal users and shippers against storing fine coal. Some have even advocated that only large lumps should be transported on shipboard and that these should be carefully packed by hand. The covering of coal piles with slack is to be avoided, also the coal should be handled as little as possible to avoid disintegration, for, in handling, the finer particles gradually sift down to the bottom of the pile where they accumulate and are a source of danger, inasmuch as at the center and bottom of the pile the most favorable conditions for spontaneous ignition exist. Here the coal is sufficiently insulated by the surrounding coal so as to retain all the heat that is generated. Air is accessible in sufficient amounts to cause oxidation, and still is not present in large enough amounts to conduct away the heat. The fact that friable coals are more prone to ignite spontaneously than coals not so friable, also seems to substantiate the above opinion. Dennstedt and Bünz in their work on this subject even went so far as to make a friability test on all the coals they worked with, for they conceded the danger arising from the fine coal with its great avidity for oxygen, and recommended that they considered safe to transport on board ship only those coals passing a certain standard in their friability test.

6. *Occluded Gases in the Coal.*—While it is now a well known fact that gases of an inflammable nature are occluded in coal, their relation to the spontaneous ignition of coal has not yet been clearly established. Whether the gases occluded in the coal are the real cause of spontaneous ignition is doubtful, but if the coal becomes heated up by oxidation or some other cause to a temperature high enough for the oxygen of the air to unite with these gases, then it is seen that the presence of these gases constitutes a source of danger, and then coals with large amounts of gases occluded in them would be more liable to ignite than coals containing smaller amounts of these gases.

7. *The Presence of Moisture.*—Opinions differ greatly as to what part moisture in the coal plays in the spontaneous combustion of the same. Some, as Doane, believe the moisture content of the air-dry coal to be a direct index of its power to ignite spontaneously. Evidence given to the New South Wales Commission and also the British Commission shows that coal piles are more

apt to take fire during warm weather following showers than at other times, although Fayol, as a result of experimental work, claims that the influence of the weather on coal heaps has not been sufficiently marked to be observable. Erdmann and Stolzenberg believe the spontaneous combustion of coal to be due to the formation of ozone by the action of the sun on warm, sunny days following a rain, when the surface evaporation is especially great. If this is true, moisture plays a more important part in the phenomena of spontaneous combustion than has heretofore been ascribed to it.

That the presence of moisture materially assists the pyritic oxidation is generally conceded, although whether it causes an increase in temperature or merely a disintegration of the coal due to the formation of ferrous sulphate is a matter of dispute. Others believe that the only part that moisture plays is a mechanical one, where alternate freezing and thawing break up the coal into smaller particles and so expose more surface to the oxygen of the air. Again, it is thought that aside from increasing the pyritic oxidation, moisture acts as a catalytic agent between the carbon and hydrogen or unsaturated bodies of the coal and the oxygen of the air. Perhaps, as Erdmann and Stolzenberg have suggested, this reaction may consist of the formation of ozone which is immediately absorbed by the coal. This idea of catalytic action on the part of the moisture is substantiated to some extent by the fact that some coals containing minimum amounts of pyrite are nevertheless very liable to spontaneous ignition; and coals of this class, viz., the Newcastle and Scotch coals, have been known to cause fires.

8. *The Accessibility of Oxygen.*—That the combination of oxygen with the constituents of the coal causes a rise in temperature seems to be firmly established. Which particular constituent is the cause of the rise in temperature has not, however, been shown with any great degree of certainty. The presence of humic acid in the oxidized coal leads one to believe that the oxygen combines with some of the unsaturated humus bodies, such as the polysaccharides. That this humus substance is an unsaturated body is shown by the fact that it absorbs large amounts of bromine without the evolution of hydrobromic acid. In fact, Fischer goes so far as to devise a practical test to determine the safety of a coal by means of this reaction with bromine.

The idea is also held that the oxygen of the air combines directly with the carbon and hydrogen of the coal and so causes an increase in temperature. If amorphous carbon (charcoal and lampblack) can be oxidized to carbon dioxide on exposure to the air by means of bacteria, as has been proved by Potter,[1] the oxidation of the carbon of the coal is very probable.

The presence of oxygen is therefore to be avoided and the old idea of thoroughly ventilating the coal piles by free access of air is gradually being dropped, and at the present, authorities deem it advisable to keep the coal away from the air as much as possible, either by submerging it under water or storing the coal in covered concrete bins. If ventilation is used to lower the temperature of the coal, it should be through pipes, so that the cooling air cannot come in contact with the coal at all.

9. *Pressure on the Coal.*—The belief that pressure on the coal is one of the leading factors in the spontaneous ignition of coal seems to be gaining ground, and because of this fact it is advocated that coal heaps should not be any higher than 15 to 20 ft. The experience of Mr. Bush in this respect (see page 69) is certainly very startling, and in a store of that size the question is very probably one of pressure rather than radiation, although, in smaller storage units, it would probably be hard to decide whether the cause of the spontaneous combustion was due to pressure or lack of proper insulation of the heat generated within the pile.

It will be highly suggestive to compare this summary of opinions with the summary at the close of the experimental part of this work. The evidence of the oxidation of the various coal substances is there enumerated, and is in close agreement with the various investigators cited above, but the conclusions as to the part played by each is different; namely, that the oxidation (a) of the unsaturated humus bodies; and (b) of pyrites are direct contributors to the heat conditions which set in motion the more advanced and vigorous phases of oxidation. The activity of these initial stages is there designated as directly dependent upon fineness of division, moisture and accession of heat from physical or external sources. With these propositions established, the real importance of these initial activities is at once apparent and the fundamental principles which must be observed in remedial processes are made evident.

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[1] Proc. Roy. Soc. London (B), Vol. 80, p. 196.

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BULLETIN NO. 47

MAGNETIC PROPERTIES OF HEUSLER ALLOYS

BY

EDWARD B. STEPHENSON

UNIVERSITY OF ILLINOIS
ENGINEERING EXPERIMENT STATION

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UNIVERSITY OF ILLINOIS

ENGINEERING EXPERIMENT STATION

BULLETIN No. 47 DECEMBER 1910

MAGNETIC PROPERTIES OF HEUSLER ALLOYS

BY EDWARD B. STEPHENSON, FORMERLY ASSISTANT IN PHYSICS

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MAGNETIC PROPERTIES OF HEUSLER ALLOYS

I. Introduction*

The Heusler alloys, so named in honor of their discoverer, are composed of copper, manganese and aluminum, and are remarkable for the fact that, in certain proportions, they are ferro-magnetic, although the component metals are not ferro-magnetic.

The following investigation of the properties of these alloys is a contribution of data on the ultimate nature of magnetism. If the permeability of a magnetic substance could be increased, and also the hysteresis losses be decreased, it would evidently be of the greatest importance to electro-technics; hence an investigation on the ultimate nature of magnetism has a commercial importance as well as a theoretical value.

The methods of thermal analysis and photo-micrography have been used in an attempt to find relations between the magnetic and the other physical properties of the alloys. These methods have been described in considerable detail, inasmuch as they will probably be of value in the study of the whole subject of alloys, and especially in the study of steels and brasses. Thermal analysis accompanying a chemical analysis gives an insight into the nature of an alloy not possible to the latter alone, and photo-micrography is an excellent method of studying the crystalline structure on which numbers of physical properties so largely depend.

II. Historical Review

In 1901, Dr. Heusler reported[1] that he had accidentally discovered that certain manganese alloys were magnetic. While turning a certain alloy in a lathe, he had noticed that the turnings adhered to the tool. This discovery led to a general investigation of the magnetic properties of manganese alloys.

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*The thanks of the writer are due to Dr. A. P. Carman for aid and facilities, and to Dr. Chas. T. Knipp for his constant advice and kind supervision of the work.

[1] Verh. d. deut. Phys. Gesel. v. 5, p. 219, 1903.

Later, it was found by Dr. Heusler, W. Stark and E. Haupt[1] that a copper-manganese alloy itself was not magnetic, but, when mixed with zinc, arsenic, antimony, bismuth, or boron, it was more or less magnetic; and when aluminum was added, a good ferromagnetic alloy was obtained. In general, the properties of any given piece varied radically with the previous heat treatment, but the most magnetic alloy was formed when the manganese and aluminum were in the proportion of their atomic weights, i. e., manganese, 25%, aluminum 12.5% and copper 62.5%.

From this fact and also from the values of the molecular susceptibilities of certain salts, as given by G. Wiedmann[2], Liebknecht and Wills[3], and others, Dr. Heusler considered the case analogous to a salt solution in which the combination of manganese and aluminum in atomic proportions was the salt, and the copper the solvent.

The discovery of these alloys did not attract much attention in England until 1904, when R. N. Hadfield exhibited a sample at the meeting of the British Association, and soon afterwards Flemming and Hadfield[4] published the results of their investigation. In their experiments, they had made two rings which gave B and H curves similar to those of cast iron, with a maximum value for the permeability of 28 to 30 for B = 1500. They considered the magnetic properties to be due to molecular grouping and not as characteristic of the elements in themselves.

Andrew Gray[5] made a further investigation with two rods which he tested at low fields only. His specimens were fairly magnetic and improved slightly upon heating to temperatures below 400°C., but quenching from that temperature almost destroyed their magnetism. Neither vigorous tapping nor immersion in liquid air had much effect. The critical temperature was found to be about 350°C. Several quenchings produced a change in structure and, when viewed under the microscope, showed large nodules imbedded in a granular matrix.

Ross[6] working at the University of Glasgow on some specimens containing 25% manganese, 12.5% aluminum, a trace of lead, and the remainder copper, found large variations due to different thermal treatments. Prolonged heating below 100° C. had little effect, but distinct improvement was shown upon heating to 160° C., and a gradual deterioration on heating further to 220° C. Testing while immersed in liquid air showed a temporary improvement which was lost on returning to room temperature. Mr. Ross quenched his specimens at 50° intervals between 400°C. and 750°C. and then tested them, (1) as quenched, (2) in liquid air, (3) back at room temperature. The effect of quenching shows clearly in the permeability which gradually decreased to 550°C., dropped to a minimum of about half value at 615° C., and then rose to approximately the original value at 650° C. and above.

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[1] Verh. d. deut. Phys. Gesel. v. 5, p. 224, 1903.

[2] Lehre von Elektrizitat v 3, p. 958.

[3] Ber. d. deut. chem. Gesel., v. 33. p. 448, 1900.

[4] Roy. Soc. London. Proc., ser. A, v. 76, p. 271, 1905.

[5] Roy. Soc. London, Proc., ser. A, v. 77, p. 256, 1906.

[6] Roy. Soc. Edinburgh, Proc., v. 27, p. 88. 1906-07.

The magnetostriction was carefully measured by Austin[1] and found to give, for his particular specimen, a value $\frac{dl}{l}=11\times 10^{-7}$ for a field of 400 c. g. s. units, which is about one-third that for cast iron. The curves showing the relation of the magnetostriction to the field strength had the same general form as the magnetization curves, though rising more slowly.

Guthe and Austin[2] found expansion curves similar to the magnetization curves and a numerical value about one-half that for soft iron. In general, the softer samples gave the greater expansion.

McLennan[3] found the continuous shortening, especially in strong fields, observed by Austin[4], and marked effects due the heat treatment and the difference in lengths of time after casting. The maximum elongation was observed in specimens having the manganese and aluminum in the proportion of their atomic weights. The permeability of some rings was found to vary greatly with the quenching temperature and was much greater when they were quenched from near their melting point than from a red heat.

Guthe and Austin[5] also tested their samples for Young's modulus and found it very large, although no exact results could be determined on account of flaws in the material.

Bidwell has shown, for iron and nickel, that there is a change in the thermo-electric power proportional to the magnetic expansion corrected for mechanical stress, but Guthe and Austin found no such effect for the Heusler alloys, even for a temperature difference of 100° C. Mendenhall reported in a private letter to them that he could find no evidence of the Kerr effect.

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[1] Ber. d. deut. Ges., v. 6, p. 211, 1904.

[2] U. S. Bur., Stds., Bul. 2, p. 297, 1906.

[3] Phys. Rev., v. 24, p. 449, 1907.

[4] ibid.

[5] ibid.

Hill[1] tried heating to various temperatures and found the effect reversible up to about 375° C., but at 500° C., irreversible.

In a discussion of the theory, Hill suggests that manganese may really be a magnetic substance under the proper conditions, as a consideration of the atomic susceptibilities and molecular magnetism of certain substances would indicate.

Defining "atomic susceptibility" as the mean susceptibility of the space containing one gram atom of substance in 1000 cc., Meyer[2] gives the following arrangement of elements in the order of their atomic susceptibilities: Ho, Er, Gd, Mn, Fe, Sa, Co, Yt, Nd, Ni, Pr. Liebknecht and Wills[3] give the following list of magnetic susceptibilities for certain salts:

Substance	k
Copper nitrate	.00163
Ferric nitrate	.01352
Ferrous sulphate	.01272
Manganic nitrate	.01536
Manganous sulphate	.01514

Yager and Myer[4] give the following values for the molecular magnetism of certain elements:

Substance	$I_m \times 10^6$
Nickel	2×2.5 c.g.s.
Cobalt	4×2.5 c.g.s.
Iron	5×2.5 c.g.s.
Manganese	6×2.5 c.g.s.

McLennan and Wright[5] studied the susceptibilities of several salts of the metals, copper, manganese and aluminum, and found approximately the same values given above with the additional value of —0.00018 for $Al_2(SO_4)_3$ and +0.00002 for $Al(NO_3)_3$. When combined in the proportions of the Heusler alloys, the susceptibilities followed the simple additive law and changed but little with concentration.

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[1] Phys. Rev. v. 21, p. 335, 1905.

[2] Ann. d. Phys., v. 68, p. 325, 1899.

[3] " " " v. 1, p. 178, 1900.

[4] Wiener Ber., v. 106, pp. 504, 623, 1897; v. 107, p. 5, 1898.

[5] Phys. Rev., v. 24, p. 276, 1907.

Hill[1] suggests that there is a simple explanation of many of the phenomena of the Heusler alloys in the allotropic theory of Osmond[2]. Thus iron shows the allotropic forms:

Alpha—soft, magnetic and stable below 700–780°C.,
Beta–hard, non-magnetic and stable between 750°C. and 860°C.,
Gamma—soft, non-magnetic and stable above 860° C.

In passing from one form to another, there is a transformation point, e. g., the common recalescent point in iron.

Nickel has only two known allotropic forms:

Alpha—magnetic and stable below 340° to 360° C.,
Beta—non-magnetic and stable above 360° C.

The transformation point can be depressed by alloying with another metal and the amount of depression is proportional to the amount of the substance added. Thus it is possible that the form of manganese stable at ordinary temperatures is non-magnetic, but that the alloying produces another allotropic form that is magnetic.

Zahn and Schmidt[3] studied the Hall effect and allied phenomena, chiefly the thermo-magnetic effect of Nernst and Ettingshausen[4], for the Heusler alloys and their individual constituents. They found the following values for the coefficient R of the Hall effect and for the coefficient Q of the thermo-magnetic effect.

Substance	$R \times 10^5$	$Q \times 10^6$
Heusler alloy	+ 1300	— 500*
Manganese	— 93	— 15
Aluminum	— 40	+ 20
Copper	— 50	+ 90
Lead	+ 9	+ 5
Iron	+ 1080	+ 1050

It is evident that the values of R and Q are not additive for the

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[1] Phys. Rev. V. 24, p. 276, 1907.

[2] The Crystalization of Iron and Steel, Mellor, pp. 12–15.

[3] Verh. d. deut. Phys. Ges., v. 9, p. 98, 1907.

[4] Wied. Ann., v. 29, p. 343, 1886.
" " v. 31, p. 760, 1887.

*The values for the alloy are average and approximate. The iron is inserted for comparison.

Heusler alloys, and comparison with iron shows no certain relation of sign or magnitude. The temperature coefficients of R and Q were found to be $+0.003$ and -0.006, respectively. Four other allied effects were detected, but not with enough certainty for quantitative measurement.

Recently, Knowlton[1] has succeeded in making specimens of especially good and uniform mechanical properties. He did not find any simple relation between composition and magnetic properties, and suggests that the copper has a much larger influence than is usually attributed to it. He made a study of the structure by means of photo-micrographs. Three distinct types of crystals were evident: (1) bright ones, unaffected by the etching fluid (HCl and $FeCl_3$); (2) dark ones, deeply etched, and (3) yellowish ones of the nature of a matrix. Crystals of the first type were evidently the magnetic ones, as no specimen from which these were absent was magnetic, and the value of I could be estimated with a fair degree of approximation from the area of these crystals. He found, also, no evidence of recalescence, and that the critical point for one specimen was 0° C. and for the others about 200° C.

III. TEST PIECES

1. *Preparation.*—Considerable time was spent in preliminary experiments with small quantities of copper, manganese and aluminum in order to learn the best method of alloying and casting. The test pieces were finally prepared in the following manner.

The materials were all tested qualitatively for iron, cobalt and nickel and found quite free from these, although they showed some carbon. Each combination of the metals was weighed out in a given proportion so as to make a total of about two pounds, melted in a brass furnace at the University foundry, and cast in fine sand molds. The melting crucible was a new clay-graphite one. The manganese and copper were put in first, and when they were thoroughly fused the aluminum was put in, a flux added, the mixture stirred with a well seasoned hard wood stick, and then quickly poured into vertical molds. Two rods, each 45 cm. long and 1.1 cm. in diameter, were poured from each melt and allowed to cool slowly in the molds.

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[1] Phys. Rev., v. 30, p. 123, 1910.

The ends of the rods, which were enlarged in the casting, were cut off and the whole length dressed down on an emery wheel to the form of a very prolate ellipsoid. The specimens were tested magnetically as cast, and again after grinding, and the grinding was shown to have had no effect upon them. Twelve samples, about 35 cm. long and 1 cm. in diameter, were thus prepared. None of the specimens could be satisfactorily worked and those with the larger per cent of manganese and aluminum were especially hard and brittle.

The magnetometer method was chosen as being best adapted to all parts of the investigation. A diagram of the apparatus is shown in Fig. 1. The resistance of the magnetizing coil was so high that 110 volts gave only two amperes through it, so this source of current was used for most of the work, but when a very small current was desired, storage batteries could be cut in at the switch S_1. The current was led through a 0–5 ammeter, reading to hundredths, and through an extra compensating coil C_2 to a reversing switch S_2, then through two control resistances, R_1 and R_2, and by the switch S_3, either through the coil C_1 alone, or through it and the magnetizing coil, MC in series. The extra compensating coil C_2 was made necessary by a small permanent field due to the wiring and the various instruments, and its position was located by trial. By means of the switch S_3, the magnetizing coil could be cut out and the coil C_1 used as a calibration coil, without change of position. Control magnets were used, so that

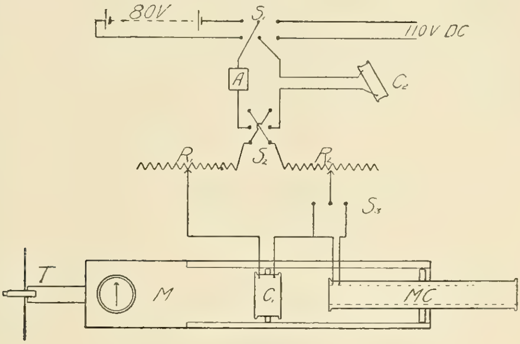

FIG. 1.

the field was about 0.275 c.g.s. The ammeter, switches, resistances, etc., were placed on a convenient table about two meters back of the magnetometer, while the magnetizing and compensating coils and the magnetometer were placed on a slideway about three meters long, clamped to a pier. The magnetizing coil was made one meter long with an average diameter of 9.2 cm., and was wound with two layers of No. 30 copper wire, on a copper water jacket with a water space of about 1 cm. For testing the specimens at higher temperatures, an electric furnace could be slipped inside the water jacket. The furnace consisted of a porcelain tube of 1.3 cm. inner diameter, on which was wound, bifilar, a nickel wire. The heating coil was covered with magnesite and placed inside a fire-clay tube which fitted closely inside the water jacket. The bifilar winding eliminated most of the field due to the heating current, and as soon as the coil reached about 350° C., the nickel lost its magnetic effect. For this arrangement of the magnetometer, the following formulas were used.

If

H_e is the earth's field as determined with the calibrating coil, then

$$H_e = \frac{2\pi n a^2 I}{10 r^3} \cot \psi \quad \ldots\ldots\ldots\ldots \quad (1)$$

where n = the number of turns, a = the radius of the coil, d = the distance of the coil from the magnetometer, $r = \sqrt{(d^2 + a^2)}$, D = the distance of the scale from the mirror, $\cot \psi = \frac{2D}{\text{def.}}$ In the magnetizing coil

$$H = \frac{4\pi n I}{10 l} \quad \ldots\ldots\ldots\ldots \quad (2)$$

where n = the total number of turns, l = the length of the coil, and I = the current in amperes.

On the assumption that the magnetic length is two-thirds the actual length,

$$I = \frac{3\left(r^2 - \frac{l^2}{9}\right)^2 H_e \tan \phi}{4 \pi a^2 l r} \quad \ldots\ldots\ldots \quad (3)$$

where I = the intensity of magnetization, l = the length of the specimen, $2a$ = the diameter of the specimen, r = the distance from the center of the specimen to the magnetometer, and $\tan \phi = \frac{\text{def.}}{2\,D}$

2. *Composition.*—The specimens were made up with the idea of testing some important points that had been developed in previous investigations; e. g., the effect of different percentages of manganese and aluminum, the effect of a little lead on the mechanical properties, and also the effect of a small amount of iron. Because there was considerable slag left in the crucible, it was believed that the percentage composition had changed somewhat in the process of melting, and so careful analyses of six specimens were made and the results are shown in Table 1.

TABLE 1

No.	Length cm.	Diam. cm.	Cu per cent	Mn per cent	Al per cent	Pb per cent	Fe per cent	IM* per cent
1	43.7	1.1	74.71	13.41	11.88			
2	44.2	1.1	69.78	12.48	17.74			
3	33.6	1.1	61.68	22.57	13.63	1.51		.61
4	48.0	1.1	54.83	28.11	17.06			
5	43.3	1.1	66.44	14.47	16.57		2.52	
6	23.5	1.6	62.43	23.39	14.18			

* IM is matter insoluble in HCl or HNO_3.

The analyses showed a larger percentage of aluminum than was intended, probably because the aluminum was put in last, melted very quickly, and seemed to fuse readily with the molten mass which was immediately poured into the molds without the aluminum having had much time to oxidize. The series formed by No. 1, 2, 6, and 4 had increasing percentages of manganese and aluminum, No. 3 had 1.5% lead and No. 5 had 2.5% of iron.

When the specimens had been prepared as given above, they were tested by the magnetometric method. The water jacket furnished an excellent means of controlling the temperature, as the hydrant water remained quite constant at 18° C. and this was the temperature of all the tests unless otherwise specified.

The data for the original test of a complete hysteresis cycle for No. 3 are given in Table 2 and shown graphically for the other specimens in Fig. 2 and 3. No curves are given for specimens 1 and 2, as they were so slightly magnetic as to be beyond the sensitiveness of the apparatus.

A study of the curves shows that No. 6 was the best of the series as it had the largest value of B with the least hysteresis, and Table 1 shows that it came nearest having the individual elements in the proportions of their atomic weights, i. e., copper 62.4%, manganese 23.4%, aluminum 14.2%.

TABLE 2

ORIGINAL TEST OF SPECIMEN NO. 3

I	*H*	*B*	*M*	*I*	*H*	*B*	*M*
+ 97	0.0	1220	....	—35	24.0	465	19.3
160	24.0	2030	84.6	91	34.4	1175	34.2
174	34.4	2220	64.6	167	51.6	2120	41.0
207	51.6	2640	51.2	216	68.8	2785	40.5
236	68.8	3030	44.1	188	51.6	2415	46.8
264	86.0	3400	39.5	153	34.4	1960	57.0
278	103.0	3595	34.9	132	24.0	1685	70.3
306	120.0	3960	33.0	62	0.0	778	....
375	137.4	4860	35.4	+76	24.0	980	40.3
237	68.8	3040	44.2	132	34.4	1695	49.3
216	51.6	2760	51.5	195	51.6	2500	48.5
202	43.0	2580	60.0	229	68.8	2950	43.0
188	34.4	2395	61.6	......	....	....	......
174	24.0	2210	92.2	......	....	....	......
104	0.0	1305	....	......	....	....	......

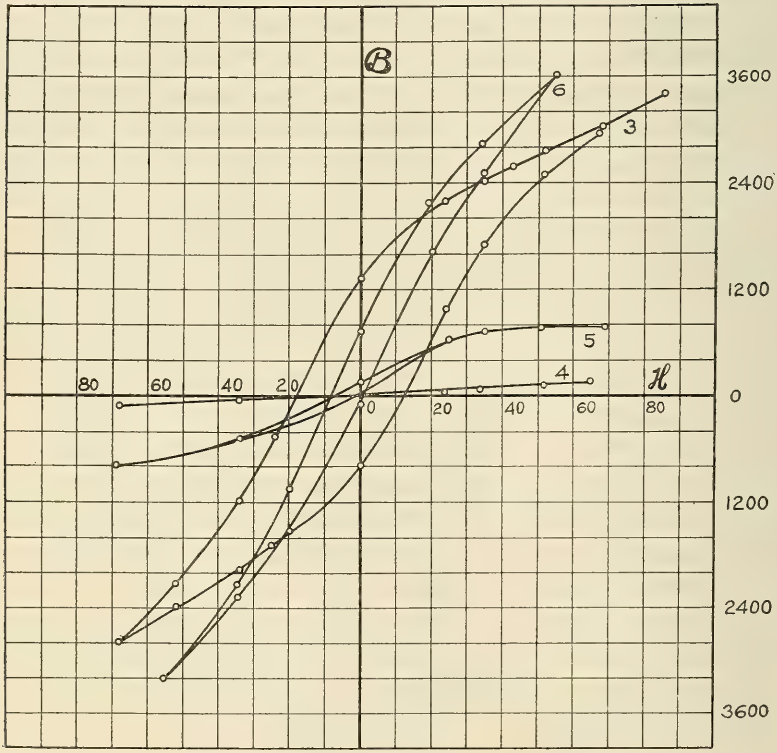

FIG. 2.

No. 3, with the lead in it, gave about three-fourths the value for B that No. 6 did and had much greater hysteresis. No. 5, with the iron in it, gave about one-third the value for B that No. 6 did, but had very little hysteresis. No. 4 which had a high per cent of manganese is only slightly magnetic.

For the purpose of comparison a few other tests gave results as shown below.

Good Swedish iron, H = 50, B = 12,000 to 14,000
Iron Wire, H = 50, B = 7,500
No. 6 alloy H = 50, B = 3,600

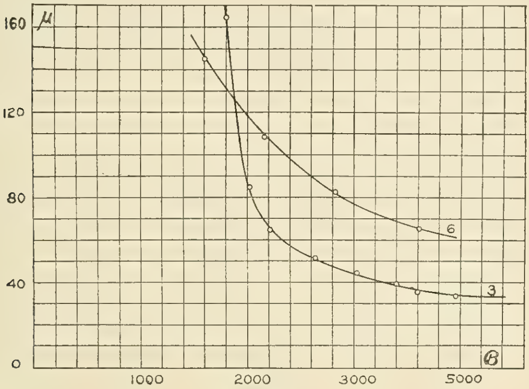

FIG. 3.

IV. TESTS

1. *Working Hypotheses.*—It was thought that in a way somewhat analogous to that of iron, the manganese, or some compound of it, in the Heusler alloys, might have two or more allotropic forms, which the alloying rendered magnetic at ordinary temperatures. Also, if the alloys were the most magnetic when the components were in the proportions of their atomic weights, it seemed possible that some compound might be formed which was the magnetic substance.

2. *Preliminary Tests.*—To test the first hypothesis, specimen No. 4 was cut into six pieces about 8 cm. long, placed in an Heraeus electric furnace and slowly heated. At each 100° interval, the temperature was kept constant for at least fifteen minutes, and then one piece was taken out and quickly quenched in water.

The theory of quenching is that the substance remains in the molecular condition that it was in at the temperature from which it was quenched.

It was found that when quenched between 300°C. and 400°C., the specimen was slightly magnetic; between 500° C. and 650° C., non-magnetic; and above 700° stronger than the original. These tests were simply qualitative, as the specimen was suspended by a thread and then placed between the poles of a horse-shoe magnet. The tests were repeated several times and were consistent. Quenching in the field of a Du Bois magnet of about 5,000 lines per square centimeter was also tried. It seemed to make no difference in the permanent magnetism, whether the pieces were quenched in the field or put in the field after being quenched.

Because the quenching in water cracked the specimens and made them very brittle, cooling in air was tried and found to produce the same result as quenching in water from a somewhat lower temperature.

3. *Effect of Quenching on Magnetic Properties.*—For more careful tests, the strongly magnetic pieces, No. 3 and 6, were used. They were heated to the temperature shown, in the order of the

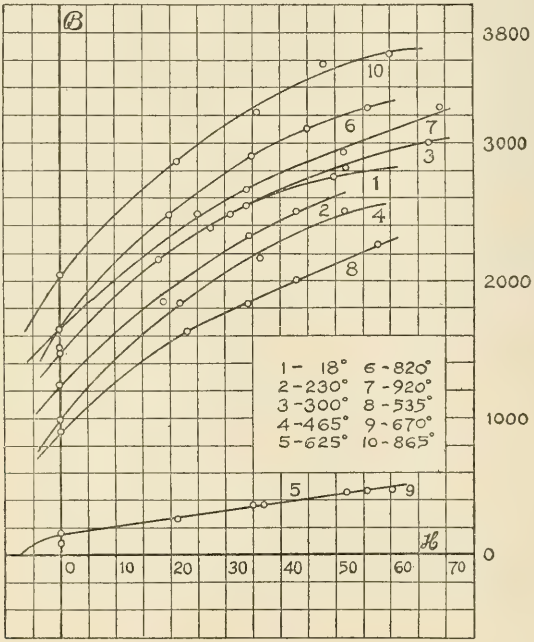

FIG. 4.

numbers of the curves, allowed to cool in air, and tested at 18°C. The results for No. 3 are shown graphically in Fig. 4, and the results for No. 6 are plotted in Fig. 5. In order to simplify the figures, the upper fourth only of the hysteresis curve is plotted from the data for the complete cycle.

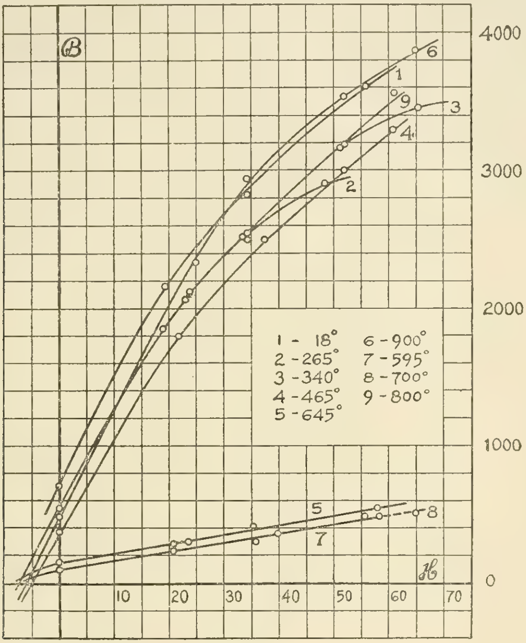

FIG. 5.

A study of the curves makes several generalizations possible. It is quite evident in both figures that when the specimen is heated to temperatures between 600°C. and 700°C. and allowed to cool in air, B is reduced to about 15% of its former value.. On heating to still higher temperatures, B regains its former value and when quenched from within 100° of the melting point of the specimen, gives the highest value obtained. No. 3 has a lower value of B but a larger hysteresis and retentivity than No. 6. The retentivity increases in about the same proportion as B. To show the effect of quenching in another way, the values of permeability M, for H = 50, are plotted against quenching temperatures in Fig. 6.

Both curves show minimum values between 600°C. and 700° C. and larger values for the higher temperatures. The values of M around 250° C. are low. This is the temperature at which it has always been noticed that the beneficial effects of baking are lost.

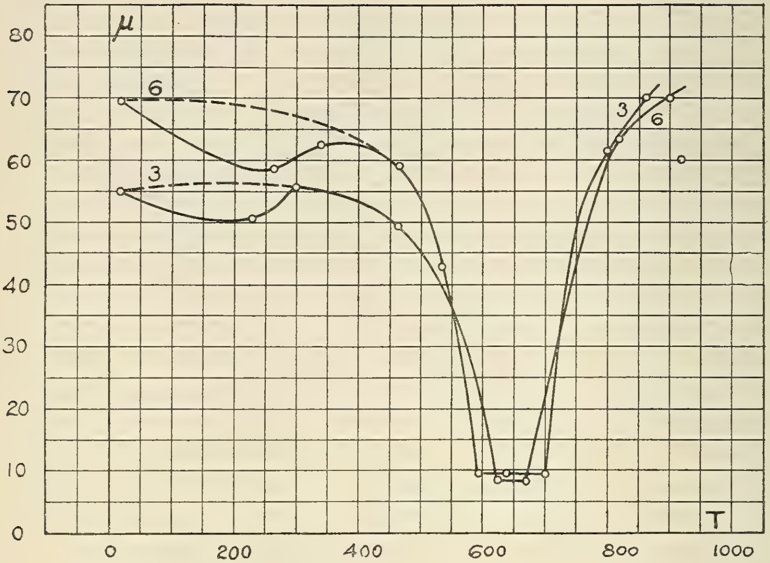

FIG. 6.

After the above series of tests of heating to a given temperature and cooling in air, specimen No. 3 was heated to several high temperatures and quenched in water. As mentioned above, the effect was much the same as cooling in air, although in the latter process there would undoubtedly be time for a limited transformation, thus making the effective air quenching temperature somewhat lower than that actually read.

Quenching No. 3 in water after heating for 20 minutes at 870°C. gave the highest value ever observed for B.
For $H = 69$, $B = 4{,}500$, $M = 65$ and for $H = 52$, $B = 4{,}300$, $M = 83.2$.

These data seem to emphasize the point that the alloy is in its most magnetic state in the molecular condition existing near its melting point.

V. THERMAL ANALYSIS

It is evident that there is something peculiar about the condition of the alloy between the temperatures of 600°C. and 700°C., and in the hope of throwing some light on this and on the hypothesis that a chemical compound might be formed, a limited thermal analysis was undertaken. The general method of thermal analysis consists in heating the substance above its melting point, allowing it to cool under constant conditions, and taking time and temperature readings at regular intervals. From the form of the curve obtained, it may be possible to draw conclusions regarding the composition and molecular arrangement of the substance.

The particular method and some of the apparatus was that used by Clement and Egy[1] in the calibration of their thermocouples.

A cross-section of the electric furnace used by them is shown in Fig. 7. It has the heating coil on the inside of the furnace.

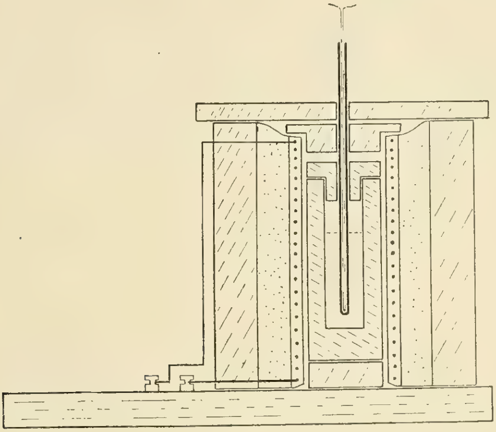

FIG. 7.

The coil of heavy nickel wire was wound on a sectional wooden core and plastered over with magnesite mixed with glue. When this had hardened, the core was removed and the coil put inside two cylinders of magnesite, the intervening spaces being filled with calcined magnesia. A large barrel of water with two iron grids for electrodes, the upper one being movable, was used as a control resistance for the furnace. The furnace would carry a maximum current of about 30 amperes on 110 volts.

The specimen for which a cooling curve was to be made was put in a graphite crucible and covered with powdered charcoal to give a reducing atmosphere. The crucible was made from a graphite rod turned to the required size in a lathe, and fitted rather closely inside the furnace.

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[1] University of Illinois Engineering Experiment Station Bulletin No. 36.

The thermocouple was enclosed in a quartz tube of 2 mm. internal diameter, the wires being insulated from each other by mica strips. This tube passed through holes in the lids of the furnace and crucible and was pushed down to within 2 cm. of the bottom of the crucible when the charge was melted.

The e. m. f. of the couple was balanced against that of a Weston standard cell by means of an Otto Wolff potentiometer arranged to be direct reading. This is shown diagrammatically in

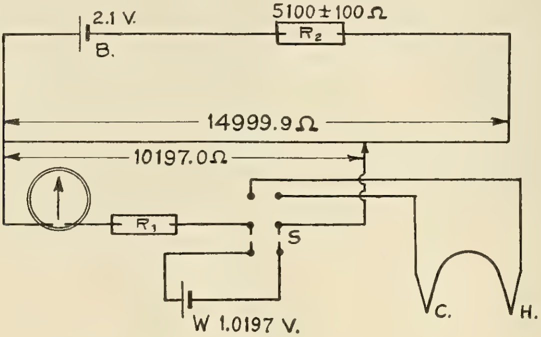

FIG. 8.

Fig. 8. The dials of the potentiometer were set on the numbers corresponding to the e. m. f. of the standard cell and the auxiliary resistance in series with the battery and potentiometer adjusted for a balance. This balance was sensitive to 1 ohm in 20 000 ohms.

Thermocouple readings were taken in microvolts (MV) and the figure in the last place was found from the galvanometer reading. The resistance in series with the galvanometer and the scale distance were so adjusted that a deflection of one scale division corresponded to one microvolt. It was thus possible to read to 1 MV at 10 000 MV.

The thermocouple used was made of platinum-platinum, 10% rhodium, and was carefully calibrated at the freezing points of three pure metals which are accurately known—zinc 419°C., silver 961.5°C. and copper 1084°C.

When time-temperature readings are taken on a pure substance as it cools from the liquid state, the temperature of the substance falls with that of the furnace until the freezing point is reached. There it remains constant until all the substance is frozen and then quickly falls to that of the furnace again. It has been found experimentally that the freezing point is much more definitely marked than the melting point, and that it is much easier to keep conditions constant when cooling than when heating.

The calibration data for the couple used are given in Table 3.

The temperature was assumed to be a parabolic function of the e. m. f. as expressed by the equation

$$T = a + bE - cE^2$$

Table 3 gave three pairs of readings for T and E, from which the three constants in the equation were determined and a temperature-microvolt curve calculated. For this couple the equation was

$$T = 118.067 + 0.128478E - 2.40282 \cdot 10^{-6}E^2$$

For small intervals MV are approximately equal to tenths of a

TABLE 3

Copper Point		Silver Point		Zinc Point	
Time	MV	Time	MV	Time	M
5:16:00	9327	2:42:00	7982	2:21	2488
:20	9280	:20	7963		
:40	9218	:40	7923		
:17:00	9150	:43:00	7875	:22	2460
:20	9094	:20	7812		
:40	9058	:40	7752		
:18:00	48	:44:00	7688		
:20	52	:20	70	:23	2455
:40	51	:40	64		
:19:00	50	:45:00	63		
:20	50	:20	62	:24	55
:40	50	:40	59		
:20:00	49	:46:00	46		
:20	47	:20	7580	:25	55
:40	40	:40	7470		
:21:00	10	:47:00	7380		
:20	8940	:20	7300	:26	53
:40	8700	....	....		
:22:00	8594	....	....		
:20	8490	....	....	:27	2447
:40	8400	....	....	....	......

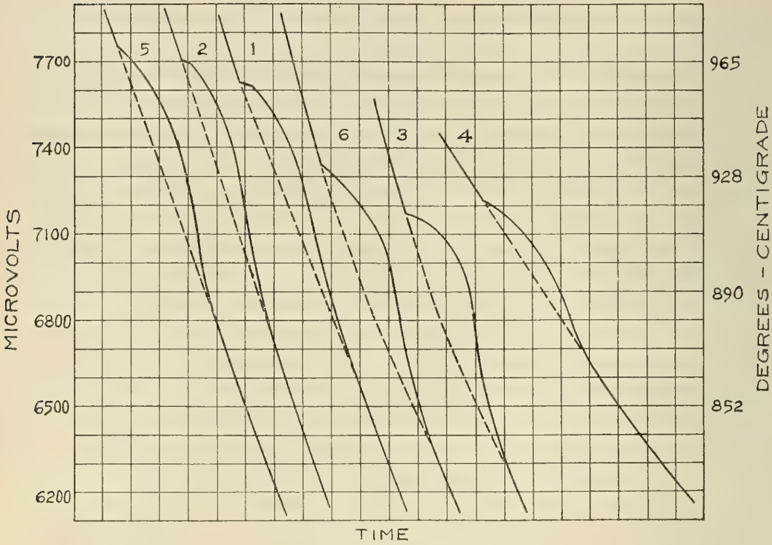

FIG. 9.

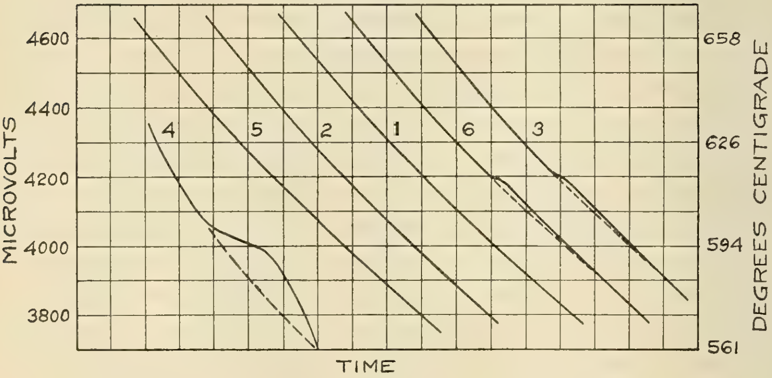

FIG. 10.

degree and it was thus possible to read to 0.1° at 1000°C., although the absolute value of the temperature was probably not closer than ± 1°.

The specimen of alloy to be tested was broken into small pieces, put into the crucible, covered with powdered charcoal, and heated in the furnace. It was kept above the melting point for

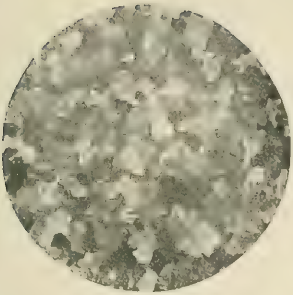

FIG. 11*. Specimen 1, twice recast, no further heat treatment. Etched with $FeCl_3$. Very slightly magnetic.

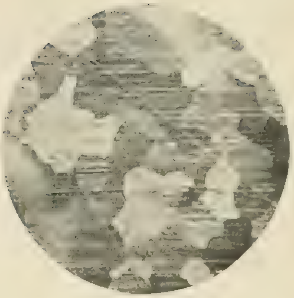

FIG. 12. Original specimen 1, heated for 1 hour at 880° and quenched. Etched with $FeCl_3$. Non-magnetic.

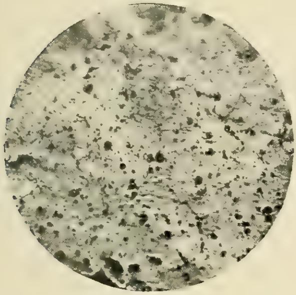

FIG. 13. Same as in FIG. 12, repolished and etched with HNO_3.—Blank pits are due to imperfect surface.

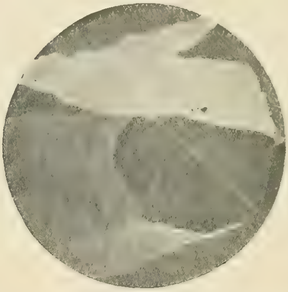

FIG. 14. Specimen 2, twice recast, no further heat treatment. Etched with $FeCl_3$. Very slightly magnetic.

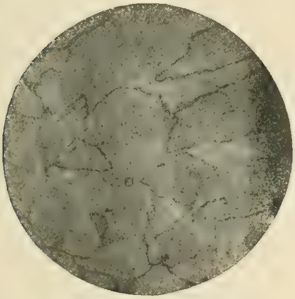

FIG. 15. Specimen 2 heated for two hours at 415° and quenched in water. Polished not etched. Very slightly magnetic.

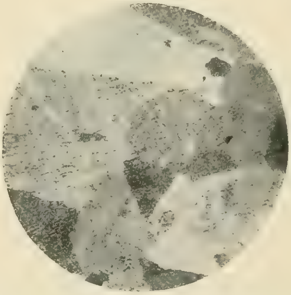

FIG. 16. Specimen 2 heated for 3 hours at 575° and quenched. Etched with $FeCl_3$. Very slightly magnetic.

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* All temperatures Centigrade.

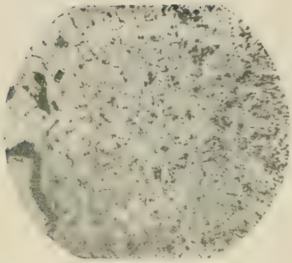

FIG. 17. Original specimen 3 heated for 1 hour at 345° and quenched. Polished but not etched. Strongly magnetic.

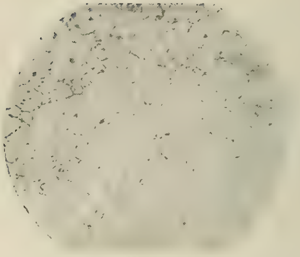

FIG. 18. Original specimen 3 heated for 4 hours at 425° and quenched. Polished not etched. Almost non-magnetic.

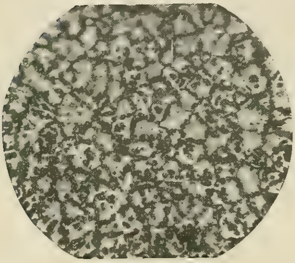

FIG. 19. Same as FIG. 18. Etched with HNO_3 and slightly repolished. Almost non-magnetic.

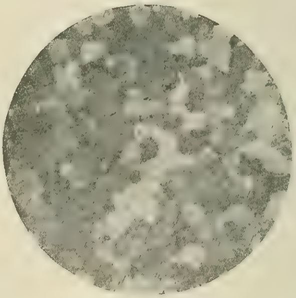

FIG. 20. Specimen 3, twice recast, no further heat treatment. Etched with $FeCl_3$. Strongly magnetic.

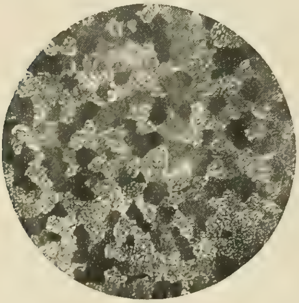

FIG. 21. Specimen 3 heated for 30 minutes at 466° and quenched. Etched with $FeCl_3$. Only slightly magnetic.

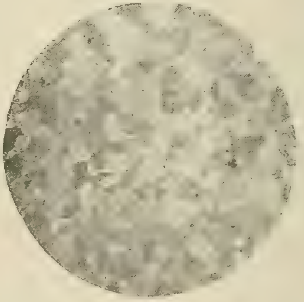

FIG. 22. Specimen 3 heated for 3 hours at 495° and quenched. Etched with $FeCl_3$. Strongly magnetic.

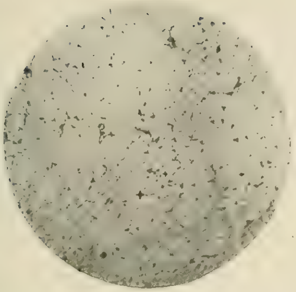

FIG. 23. Original specimen 5 heated for 2 hours at 620° and quenched. Etched with HNO_3. Slightly magnetic.

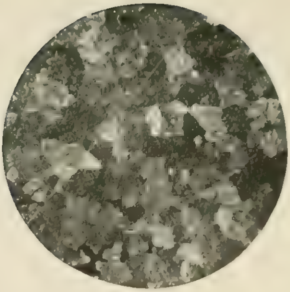

FIG. 24. Original specimen 5 heated for 2 hours at 880° and quenched. Etched with $FeCl_3$. Very slightly magnetic.

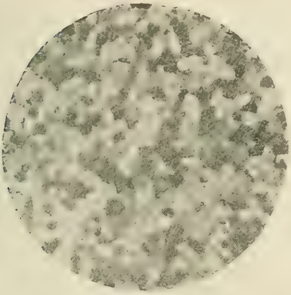

FIG. 25. Specimen 5, twice recast, no further heat treatment. Etched with $FeCl_3$. Slightly magnetic.

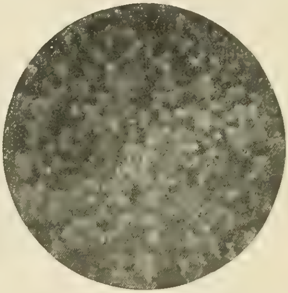

FIG. 26. Specimen 6, twice recast, no further heat treatment. Etched with $FeCl_3$ Strongly magnetic.

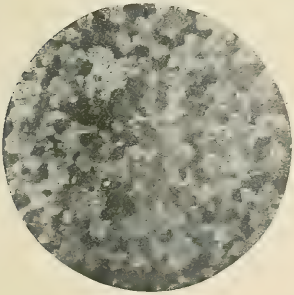

FIG. 27. Specimen 6 heated for 30 minutes at 470° and quenched. Etched with $FeCl_3$. Only slightly magnetic.

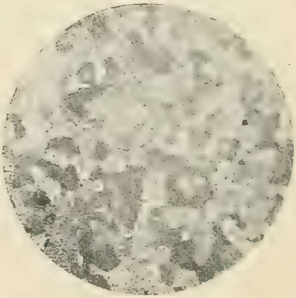

FIG. 28. Specimen 6 heated for 3 hours at 590° and quenched. Etched with $FeCl_3$. Strongly magnetic.

TABLE 4

COOLING CURVE DATA FOR SPECIMEN No. 3
READINGS TAKEN EVERY 20 SECONDS

Time	MV	Time	MV	Time	MV
3:30	7628	3:45	5417	4:00	4192
	7572		5383		73
	08		46		53
:31	7440	:46	10	:01	38
	7376		5272		18
	10		40		4097
:32	7240	:47	04	:02	..
	7173		5170		.
	63		37		4040
:33	57	:48	03	:03	14
	50		5073		3996
	37		40		78
:34	.. ....	:49	07	:04	58
	08		4978		40
	7084		50		19
:35	52	:50	18	:05	00
	18		4888		3882
	6983		60		63
:36	36	:51	30	:06	44
	....		00		23
	6620		4773		03
:37	... .	:52	44	:07	3788
	6468		16		70
	00		4694		54
38	6338	:53	64	:08	35
	6280		37		18
	20		14		..
39	6172	:54	4587	:09	3684
	18		62		..
	6072		34		59
:40	24	:55	10	:10	42
	5980		4487		28
	42		63		12
:41	5893	:56	38	:11	3595
	55		14		80
	12		4392		67
:42	5773	:57	66	:12	52
	30		45		33
	5693		22		18
:43	50	:58	00	:13	00
	11		4280		3486
	5573		59		70
:44	30	:59	37	:14	54
	5490		19		37
	55		02		22

some time, to allow the pieces to fuse together, then the couple was pushed down into it, the heating current shut off, and readings of the potentiometer taken every 20 seconds. It took about two hours for the temperature to fall to 300°C.

When it was desired to pass very slowly through a point, the heating current was merely reduced, and, in order to keep it constant, the storage batteries were "floated on the line". The battery of forty cells was charged with a current of, say 16 amperes, while a current of 18 amperes was taken from it. This current would remain quite constant for several hours.

The cooling curve data for the six specimens are shown in Fig. 9 and Fig. 10, the curves in each figure being numbered to correspond with the specimen. Microvolts are plotted as ordinates and time as abscissas. The squares in the figure are centimeters and 1 mm. is equal to 10 sec. so the points are too close together to be shown in the figure.

VI. Discussion of Cooling Curves

The upper parts of the cooling curves are plotted in Fig. 9 and the lower parts in Fig. 10. In the intervening region, the specimen cooled regularly with the furnace. The various curves show four characteristic regions, viz., (1) an almost straight line where the molten liquid is cooling with the furnace; (2) an abrupt change to an almost horizontal line, curves 1 and 2, Fig. 9, which indicates that a pure substance is freezing out of the solution; (3) a rounded portion with a quick drop to the temperature of the furnace which is given by the dotted line; (4) another abrupt change in slope in curves 3, 4 and 6, Fig. 10, which indicates a transformation, or recalescence point.

All the curves are those generally characteristic of solid solutions, but there are not enough data to draw any conclusions as to the formation of a compound. It was noticed that when an alloy was at the temperature represented by the bulge in its curve in Fig. 9, it was possible by pressing a rod into the crucible, to squeeze a liquid out of the semi-solid mass much as water can be pressed out of a sponge.

The data for each curve were taken at least twice and the freezing points found to be quite constant. The depressions of the freezing points are in the order of increasing percentages of manganese, except No. 5, which is high, possibly on account of the 2.5% of iron in it, and No. 3, which is low, due to the 1.5% of lead in it.

Curve 4, Fig. 10, has an exceptional transformation point. The test piece for it was made of the small pieces of No. 4 used in the preliminary quenching tests above. When the specimen had cooled to about 595°C., a pronounced change evidently took place, for there was a distinctly audible cracking, and on examination, the charge was found to be very loose in the crucible and the contraction had crushed the quartz tube containing the thermocouple.

Curves 1, 2 and 5 do not show any transformation points, but curves 3 and 6 do, and this point is at the same temperature, 615°C., from which these specimens were non-magnetic on quenching. It is evident then that at this temperature and for specimens of the approximate composition of No. 3 and 6, there is a molecular rearrangement accompanied by an evolution of heat, and that when kept in this state by quenching, the alloy is non-magnetic, but if it is allowed to cool slowly to room temperature, it goes over into a magnetic form.

VII. Photo-Micrography

Since it is generally agreed that the magnetism of substances is due to their molecular arrangement and since even superficial examination of these alloys showed changes in crystalline structure with the heat treatment, a study by means of photo-micrography was carried out This method has not been very generally used and specific directions are hard to find, so it will be described here somewhat in detail. A general account of the art of photo micrography will be found in the Appendix.

The apparatus consisted of a Leitz "New Universal Photo-Micrographic Apparatus" fitted with an incandescent gas lamp, a microscope with a wide tube, and an opaque vertical illuminator. The magnification could be adjusted to any desired ratio by a suitable combination of eye-piece, objective and length of camera bellows. The magnification at which the accompanying photographs were taken was determined exactly by taking a photograph of a standard grating and counting the number of lines per cm. in the picture.

It is necessary that the specimen should have a plane surface and a high polish in order to give a flat field for the microscope. This was accomplished by fixing the pieces in a block of wood and grinding them on a series of rapidly rotating disks covered with emery paper of increasing fineness and then grinding by hand on a glass plate charged with emery. Emery sufficiently fine for this purpose was obtained by shaking "flour" emery in water and decanting the liquid with the particles in suspension after allowing it to settle for various lengths of time from one minute to twenty-four hours. This grinding gives a plane surface but covered with very fine scraches.

To remove the scratches the specimen must be polished. Great care is necessary not to destroy the plane surface or make more scratches by a little grit or dirt getting on the polisher. First, a felt wheel charged with "Tripoli" was used, then a cotton buffer, and finally the process was finished by hand by rubbing on a linen cloth stretched over a glass plate and charged with jeweler's rouge. This process might be much simplified and hastened by using a good mechanical grinder and polisher, but the final work by hand, though rather tedious, seems to give the finest surfaces. Excessive polishing should be avoided because the rapidly rotating polisher seems to cause the metal to flow over a thin surface layer entirely obscuring the structure.

To bring out the structure clearly, it is usually necessary to "etch" the specimen, i. e., to use a reagent that will attack some parts more than others. The particular etching fluid must be determined by the composition of the substance studied. For the Heusler alloys, a dilute solution of nitric acid or a strong solution of ferric chloride with possibly a little hydrochloric acid added, was used to bring out the various points.

In taking the pictures, artificial light diffused by a ground glass screen was used in preference to daylight because of its greater constancy and ease of control. Stopping down the light and using a longer exposure gave more detail and sharper contrast. The focusing was accurately done with a lens and a fine adjustment.

The plates used were Standard "Orthonon", which are orthochromatic and non-halation. Because of the double film, the plates were developed slowly and until almost black, and left in the hypo and washed about twice as long as ordinary plates.

A printing paper with a glossy enameled surface was used to bring out the contrast in the structure. This glossy paper usually requires a special non-abrasion developer.

PHOTO-MICROGRAPHS OF THE HEUSLER ALLOYS

A large number of photographs were taken under various conditions and a few, which are all of a constant magnification of 50 diameters, are given in Fig. 11 to Fig. 28. The "original" specimens are pieces of those first cast and whose composition is given in Table 1. The others were made from the original ones of the same number by melting and recasting twice. This produced more homogeneous alloys with better mechanical properties. There was some slag formed at each melting, so the composition is probably not quite the same as the original, but they did not differ much, as the slag was of approximately the same composition as the specimen and was magnetic.

After a specimen had been heated and quenched, it was ground off for at least 2 mm. below the surface and care was taken to keep it from heating too much during the grinding.

The magnetic testing for this part of the work was done qualitatively by suspending the specimen by a thread in the field of a large permanent magnet. Slightly magnetic means that the specimen would orient itself with the field and possibly turn through an angle of 90° as the magnet was rotated. Strongly magnetic means that the specimen could be lifted by the magnet.

Some of the photographs show the three types of crystals described by Knowlton[1], but no such simple relation as he found between the size of the white crystals and the magnetization could be determined. In fact there seemed to be no essential difference between specimens 3 and 6 when quenched from the temperature that made them non-magnetic and when taken in their originally strongly magnetic condition. Also it would be difficult to distinguish between Fig. 11 and Fig. 22, although the former is of specimen 1 which was almost non-magnetic and the latter is of specimen 3 which was strongly magnetic.

The photographs of specimen 2 show a peculiar arrangement of long slender crystals pointing towards the center of the specimen where the crystals are smaller and more regular. The recast specimens all show much smaller crystals than the original ones, but none of them shows the pronounced effects due to quenching or annealing that were expected.

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[1] Phys. Rev., v-30, p. 123, 1910.

VIII. SUMMARY

The results of this investigation may be summarized as follows:

(1) The best specimen had the manganese and aluminum in the proportion of their respective atomic weights. It gave a maximum value of $B = 4000$ and $M = 57$ for $H = 70$, but had not reached saturation.

(2) Heating to various temperatures, cooling in air and testing at room temperature gave, for $H = 50$, a practically constant value for the permeability from room temperature to 300°, a rapid drop between 300° and 600° to about one sixth its former value, and beyond 700° a rapid rise to better than the original value at 900°. This series of changes was reversible for at least three times.

(3) The largest values of B and M were obtained when the specimen was quenched in water from near its melting point.

(4) A series of cooling curves gave melting points between 910° and 970°C., and curves characteristic of solid solutions.

The curves for the two magnetic specimens showed transformation points, with evolution of heat, at 615°C. Specimens quenched from this temperature are non-magnetic when tested at room temperature.

(5) It seems evident that there is an allotropic form of the alloy or at least of the magnetic constituent of the alloy, which has a non-magnetic molecular arrangement at about 600°C.

(6) A series of photo-micrographs showed differences in the crystalline structure due to previous history, but no simple relation could be established between the magnetization and the presence of certain crystals.

APPENDIX

PHOTO-MICROGRAPHY

The possibility of taking a photograph through a microscope was demonstrated as early as 1840, but only within the last two decades has it been possible to obtain satisfactory apparatus at moderate cost or to find books from which one could acquire a knowledge of the technique in a reasonable time. Even yet in this country photo-micrography is not so well understood or so fully applied as its advantages would warrant if better known.

It is the purpose here to give a few fundamental principles and essential points in the selection and use of the apparatus with some general methods of attack in the solution of the problems involved. Incidentally, it is well to distinguish a photo-micrograph, which is a photograph of a microscopic object, from a micro-photograph, which is a microscopic photograph of a large object.

Photo-micrography may be applied in almost any case where the microscope is used and in some cases, as will be shown later, this art has extended the field of the microscope. As a record of the objects seen in a microscope, a photograph has advantages over the usual drawing, in that it tends to eliminate the personal bias and to give increased weight to the evidence presented. It saves much time when the necessary equipment and skill are once acquired, and it may be reproduced indefinitely in the positive print or the lantern slide. It is possible by the use of ultra-violet light to photograph objects that are invisible with ordinary light; by the proper choice of plates and color filters, the brilliant shading of colored objects may be correctly reproduced in monotone; because of the cumulative effect of the light on the sensitive plate, an object but dimly seen may be plainly photographed by prolonged exposure; while by the use of the cinematograph, moving pictures of a microscopic world may be had. Some application of photo-micrography is certain to be an advantage in almost any line of modern scientific work, and to the amateur photographer, it opens up new possibilities for the application of his highest skill.

APPARATUS

The apparatus necessary for photo-micrography depends upon the grade of work to be done, but it must include a microscope, a camera, a rigid support for them, properly prepared specimens, some source of illumination with means of control, suitable plates, printing paper, developing and fixing solutions. Various home-made combinations may serve, in some instances, but for the best work, particularly at high powers, special apparatus will be more satisfactory because of the corrections of the optical system and the devices for accuracy and ease of adjustment that are so great a saving of time and patience.

Microscope.—A special microscope is not necessary, but the one used should have a wide tube for photographing without the ocular, a stable base, an adjustable stage, and the best possible lens equipment.

There are two properties of lenses that must be especially considered in photo-micrography. The spherical aberration is due to the fact that monochromatic light is unequally refracted in passing through a single spherical lens, being refracted more near the edge than it is near the axis, so that all the rays incident on the lens cannot meet exactly in the same focus. Chromatic aberration is due to the fact that the lens acts as a prism, resolving the white light into spectral colors which are unequally refracted, and thus the different colors cannot be brought to a focus at the same point. By a suitable combination of a bi-convex crown glass lens with a plano-concave flint glass (one with double the dispersive power) the chromatic aberration can be corrected for any *two* colors, but there is still a secondary spectrum left because the dispersion of the colors is not proportional in the two kinds of glass. Also the spherical aberration can be corrected for any *one* color, usually that of maximum visual intensity, but there remains under-correction for the red and over-correction for the violet. A lens of this type is called an achromatic lens. As is well known, the light that is most active photographically on the ordinary sensitive plate, the so-called "actinic" light, is that which is near and beyond the violet end of the spectrum, while the eye is more sensitive to the longer wave lengths in the yellow-green. Thus the ordinary achromatic lenses with corrections for spherical aberration in the region of maximum visual intensity and for chromatic aberration between the red and violet are not the best for photo-micrography except under special conditions.

After an exhaustive investigation by Dr. Abbe, with the co-operation of the optical workshops of Zeiss and the German government, crown and flint glass were produced of such quality that, when combined with a fluorite lens and special eye-pieces, it was possible to correct the chromatic aberration of the objective for *three* colors, thus removing the secondary spectrum, and to correct the spherical aberration for *two* colors and therefore practically for all. These lenses are so well corrected over the whole visual and photographic range as to justify the name apochromatic. Besides their almost perfect achromatization, these apochromatic lenses have the advantage of utilizing the full theoretical aperture, and of permitting a great increase in magnification by the use of special high power oculars. These lenses are especially valuable for photo-micrography.

Camera.—The camera should have a stable base and a means by which the microscope may be firmly clamped to it. A very frequent cause of indistinctness in the negative is the vibration of the supporting table. This may at least be diminished by having the camera and microscope vibrate synchronously, and it may even then be necessary to work at some time when the whole building is quiet. Another important point to be observed is that the guides and grooves for the plate holder and ground glass slide should be accurately adjusted so that the plane of the photographic plate will lie exactly in that of the glass on which the object is focused. For the final adjustment, a clear glass and a focusing lens should be used instead of the ordinary ground glass. The extension of the camera determines the enlargement, but it is the microscope that determines the *definition;* the photograph may be merely of a convenient working size. The power of the objective used should be as low as is consistent with satisfactory definition, because this is the best working condition for the microscope, and the difficulties in the photographing increase rapidly with the magnification. To obtain the magnification of a given arrangement, the simplest method is the direct measurement of the enlarged image of a micrometer microscope ruled in thousandths of a centimeter, and an analogous method is applicable in determining the actual size of an object.

Illumination.—The use of artificial light for photo-micrography is almost universal because of its constancy and ease of control; and the choice between kerosene, gas, calcium, or electric light depends upon their availability and upon the particular work.

The yellow kerosene flame, though weak, may prove very satisfactory at low magnifications with ordinary achromatic lenses and ortho-chromatic plates without a color screen, while the arc light is far more intense, rich in actinic rays, and, in general, requires apochromatic lenses and color screens. Before making an exposure, it is necessary that the light be properly focused and centered, and the field properly illuminated. This involves centering the condenser, and then centering the light and focusing the condenser until a sharp image of the light source is projected through the condenser into the plane of the object. To secure uniform illumination, it is often necessary to introduce a bull's eye condenser between the light source and the sub-stage condenser at such a point that the light will be at the principal focus of the bull's eye, thus giving parallel light. When a ground glass is used to give diffused light or a colored glass for colored light, it may be placed between the bull's eye and the condenser. The light from the microscope is then centered on the ground glass of the camera, and the circle of light should be uniformly illuminated and sharp around the edges. For instance, if there is a dim halo around the image, it may be due to a flooding of the objective with too much light, which should be reduced by means of the diaphragm in the condenser; or, on the other hand, it may be due to the use of an objective with too narrow an aperture.

Preparations.—It is assumed that the best specimens will be photographed, and the inherent difficulties of the process should not be increased by faulty technique in the preparation. In general, a flat field with clearly contrasted structure, is desirable. The depth of vision with which an object is seen in a microscope is the sum of two factors; the focal depth of the objective and the accommodation of the eye. This latter factor is absent in the photographic plate, so sharp definition is obtained only in the critical plane. No such composite image is possible as the microscopist often obtains visually by small alterations in the focus; hence the necessity for a flat field and a sharp focus.

Sensitive Plates.—As noted above, the ordinary plate is not sensitive to red and yellow light, but plates may now be obtained that are more or less sensitive to these colors and are variously called orthochromatic, isochromatic and panchromatic, depending upon their particular qualities. It is necessary that achromatic lenses be especially corrected for photography and that orthochromatic plates and often a color screen be used with them. With apochromatic lenses, ordinary plates may be used although the plates that are sensitive over the wider range are better. The red-sensitive plates must be handled in deep ruby light or total darkness. Another important correction is that for halation —a blurring of the image due to light diffusely reflected from the back of the glass plate. The manufacturers correct this by giving the plate an extra coating of absorbent film. Any plate may be rendered non-halation by "backing". A coating of caramel, colored with lamp black, is recommended. It may be applied to the glass side of the plate with a stiff brush and removed with a wad of damp cotton before development. In general, the plate should be developed for contrast and detail with considerable density. Hydroquinone and metol are satisfactory developers.

Exposure.—The time of exposure depends on so many variables that exact directions can not be given, but the following rule will be found valuable: Secure as satisfactory an arrangement as possible before exposure, determine the time of exposure by trial, and then keep the conditions constant, or at least vary only one at a time so that the effect can be calculated. This rule applies to light source and distance, magnification, plates, developer, printing paper and time of development and printing. To determine the exposure by trial, withdraw the dark slide one cm. at a time at 10-sec. intervals thus obtaining a series of strips of known exposures. When developed for an average time, there is no difficulty in determining which is the best. The development of the plate gives much information in regard to the correctness of the exposure. Although, in special cases, a negative may be intensified or reduced, it is generally better to repeat the exposure until a satisfactory negative is obtained.

The Positive.—The positive print may be either on paper or on a lantern slide. If $3\frac{1}{4} \times 4\frac{1}{4}$ plates are used, they will be very convenient for printing slides by contact. Because the light shines through the lantern slide, thus giving the variations in shading with all the wealth of detail, it is really the best kind of a positive. For printing paper, a glossy surface especially sensitized for contrasted effects, is essential and the prints may then be burnished or squeegeed.

Color Photography.—The modern idea of color photography is not to reproduce in the negative or postive print the actual colors of the object, but to get in monotone the shading which we see in the colors. If one wishes to photograph a relatively weak color with increased contrast, the general rule is to use a plate but slightly sensitive to that color, and a screen cutting off the color of the preparation. Under these conditions, the object will photograph as though it were black. On the other hand, if it is desired to decrease the effect of a certain color or "hold it back", a light of the same color should be used and a plate sensitive to that color. Thus if a red flower were photographed with a red light and a red sensitive plate, the negative would be strongly affected, but the positive would be light.

The color screens may be made of a glass cell filled with various colored liquids of different densities, or they may be made of colored glass. Several of the dry plate manufacturers have a series of screens spectroscopically adjusted to work with certain plates.

Ultra-violet Light.—The use of ultra-violet light in photomicrography has been one of the most beautiful developments in this science. A short theoretical discussion will be necessary for the proper appreciation of this point. The resolving power of a lens, i. e., its property of showing two points close together as distinct and not fused into one, is, for central lighting, directly proportional to the numerical aperture and inversely proportional to the wave length of light used. The numerical aperture in turn is directly proportional to the index of refraction of the glass and the sine of half of the angle included between the lines drawn from the principal focus to the ends of a diameter of the lens. The numerical aperture for dry mountings in air must always be less than unity, and is limited in practice to 1.50 for the best oil immersion. Thus there is a practical mechanical limit to the resolving power of an objective with any of the kinds of glass now available for lenses. Now the resolving power might be increased by decreasing the wave length of the light used, but the eye is not sensitive much beyond the violet, and, too, ordinary lens glass is opaque to the short wave lengths. Fortunately, fused quartz is transparent to ultra-violet light and the photographic plate is sensitive to it. By making all the lenses of quartz glass and producing the light by sparking between cadmium electrodes, the resolving power of a microscope may be doubled. The light from the cadmium spark has a wave length of .275 μ as compared with 0.589 μ for yellow sodium light, and is unusually monochromatic, thus eliminating the necessity of correcting for chromatic aberration. It is found also that many organic objects that are colorless under white light act as if they were colored under the ultraviolet. To render the object visible for selection and focusing, a uranium glass is used that fluoresces under the action of the ultra-violet light. The equipment for this work is rather expensive, on account of the extra apparatus necessary to produce the light, and the cost of the quartz lenses, which are monochromatic and not available for other work.

APPLICATIONS OF PHOTO-MICROGRAPHY.

Since the biologist has always made the largest use of the microscope, much of the technique of photo-micrography has been developed for his particular use and for the text-book written from his point of view, but there are other important fields of application of which two will be discussed by way of illustration.

Metallurgy.—Chemical analysis will give the percentage composition of a substance, but sometimes a wide difference in physical properties is found in substances having the same chemical composition. The application of the modern theory of solutions to solids has led to a remarkable development in our knowledge of alloys, and in this work thermal analysis and microscopic examination have been the chief aids to chemical analysis. It has been found that such physical properties as hardness, tensile strength or thermal conductivity are functions of the crystalline structure which may be seen in the microscope when the specimen is properly prepared. In the case of our best known alloy, steel, the physical properties of any given specimen are largely determined by the heat treatment, and the microscope shows that this treatment is accompanied by a definite change in structure. In the investigation described in this bulletin, an attempt was made to find a relation between the magnetic properties and the structure in the Heusler alloys, and although this was not established, there evidently is a relation between the structure and the heat treatment. When the structure associated with particular properties has once been established, a microscopical examination is a rapid and convenient test for these properties, and the photograph is a good method of recording the data.

The technique for the study of metals differs in several points from that for transparent substances. Because the metals are opaque, it is necessary to use reflected light. With long focus objectives, the illumination may be from the side, but should be as nearly vertical as possible to prevent loss by reflection. For higher magnifications, some form of vertical illumination is used. It consists generally of a prism or glass plate inserted in the microscope tube above the objective, and set at such an angle that it reflects the light received through an aperture in the side of the tube down through the objective on to the specimen. A point to be noted is that the insertion of this illuminator increases the tube length and must be compensated for in the sliding sleeve as the lens system is corrected for a given length of tube, usually 170 mm. The common microscope objectives are corrected for the thickness of the cover-glass, and hence for work with dry mountings, it is necessary to have objectives without this correction, or with a device in the objective to compensate for it.

The application of photo-micrography to the study of the Heusler alloys has been given in detail on page 23 of this bulletin, and illustrates the general methods, though each alloy requires some special treatment. With alloys of better mechanical properties, the grinding and polishing are much simpler processes than those described. There seems to be no definite rule by which one can determine the best etching agent, and a large number of acids, bases or salts may have to be tried before a satisfactory one is found. Sometimes beautiful oxidation effects can be produced by heating, and indeed, it is difficult to prevent these effects at ordinary temperatures. If the specimens are to be preserved, they may be coated with a very thin transparent varnish.

Geology.—The microscope is in common use in geology, and a series of photo-micrographs gives an unsurpassed method of comparing a number of specimens. The size and shape of rock crystals not only furnish a means of recognizing the kinds of crystals, but may enable one to estimate the temperature at which they were formed and the rate of cooling, problems of particular importance to the dynamical geologist. Many specimen can be ground thin and viewed by transmitted light and others may be seen by side or vertical illumination. The use of polarized light brings out the anisotropic optical properties and shows the axial placing of the crystals. The color effects with polarized light are most beautiful. By a suitable combination of transmitted light, reflected light and dark ground illumination with long focus planar objectives, one may obtain photographs of minute fossils that show both the external form and a certain amount of internal structure.

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RESISTANCE TO FLOW THROUGH LOCOMOTIVE WATER COLUMNS

BY

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AND
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UNIVERSITY OF ILLINOIS
ENGINEERING EXPERIMENT STATION

BULLETIN NO. 48 JANUARY, 1911

RESISTANCE TO FLOW THROUGH LOCOMOTIVE WATER COLUMNS

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RESISTANCE TO FLOW THROUGH LOCOMOTIVE WATER COLUMNS.

1. *Preliminary.*—Water is delivered to the tanks of locomotives either directly from an elevated tank or through a pipe line and a discharging device known as a water column, standpipe, or penstock. Qualifications commonly recognized as desirable in a locomotive water column are (1) the hydraulic properties of rapid discharge, moderate frictional resistance to flow, easy movement and control of valve, and freedom from objectionable water hammer; (2) a mechanical construction permitting easy and satisfactory operation and convenient inspection and repairs; (3) a design giving reasonable cost of manufacture and maintenance. With the increased importance of time in train service the importance of the first-named element in a water column is becoming recognized. Little definite information on the hydraulics of water columns has been available, so that in designing water service plants the engineer has been largely in the dark in making allowance for the head lost through the water column or even in the selection of size of water column, and the differences of practice are considerable. The American Railway Engineering and Maintenance of Way Association has appreciated the importance of having fuller information on the flow through water columns. Growing out of this interest, this investigation was taken up in cooperation with the Committee on Water Service of the Association.

2. *Scope of Bulletin.*—This bulletin gives the results of tests, made in the Hydraulic Laboratory of the University of Illinois, of fourteen water columns covering the principal types used in supplying water to locomotives in the United States. The tests were made for the purpose of determining the losses of head through the column, including the loss in the valve and in the riser and spout. Incidentally, the action of the valve in closing and the changes in pressure in front of the valve were studied with a view of getting information on the influence of the type of the valve on the development of water hammer in the supply main. A general statement of the principles of water hammer and their application to a water service installation, as well as of

relief valves, is also given.

There are also given in the Appendix diagrams for calculating the loss of head in pipe and diagrams for the loss of head in elbows, tees, and valves. These are presented with the thought that their inclusion here will be a convenience to a great many readers.

3. *Acknowledgment.*—Acknowledgment is made to the Committee on Water Service of the American Railway Engineering and Maintenance of Way Association, and especially to Mr. Robert Ferriday, Engineer Maintenance of Way, Cincinnati, Cleveland, Chicago, and St. Louis Railway, for cooperation and for arranging with the manufacturers for the use of the water columns tested, and for valuable suggestions and helpful interest throughout the tests. Acknowledgment should also be made of the fact that the Water Service men of the Peoria and Eastern division of the C. C. C. & St. L. Ry. assisted in setting up the water columns. The results of a part of the tests were embodied in a report to the American Railway Engineering and Maintenance of Way Association.

4. *Water Columns.*—The water columns were furnished by the manufacturers as representing the regular article supplied to the trade. The 10-in. size was chosen for the tests, since it is a medium size and since with this size a high velocity could be maintained through the water columns with the facilities of the Laboratory. The columns were set up by experienced water-service men. As a representative of the manufacturing company furnishing the water column was present for the types with which the men were not familiar, the proper erection of the water columns was insured.

The water columns will be designated by the Roman numerals given in Table 1, the numbers being used in the order in which the tests were made. The Poage water column is manufactured by the American Valve and Meter Co.; the Otto, by the Otto Gas Engine Co.; the Gulland, by the Best Manufacturing Co.; the Mansfield and the U. S., by the U. S. Wind Engine and Pump Co.; the Sheffield, by Fairbanks, Morse & Co.; and the Golden-Anderson, by the Golden-Anderson Co. The Sellew is a new water column designed by Mr. W. H. Sellew, Principal Assistant Engineer of the Michigan Central Railroad, and now handled by the Cleveland Railway Supply Co.; in the tests with the Sellew the experimental valve replaced the valve of the Gulland water column. In the classification, the terms globe, angle, and gate are used as roughly indicating the form of the valve. The method of operating the valve, both in the manual type and in the hydraulic type, differed considerably. The form of spout used was chosen by the manufacturer, the form used being no part of the test, since both rigid and adjustable spouts are made by manufacturers. The nozzles marked "anti-splash" are cylindrical nozzles having a reticulated diaphragm to straighten the filaments of the discharging stream. The one marked "conical anti-splash" was an open cone. The other nozzles were plain cylinders.

The tests of the first ten water columns were made in October, November, and December 1909 and the results were reported to the Committee on Water Service of the American Railway Engineering and Maintenance of Way Association. Water column XI was tested in May 1910. Water columns XII, XIII and XIV are new forms of columns, designed after the first tests were made; these were tested in January 1911.

The make-up of the water columns is shown in the cuts, Fig. 14, 16, 18, 20, 22, 24, 26, 28, 30, 32, 34, 36, 38, 40 and 42 at the end of the text.

TABLE 1.

CLASSIFICATION OF WATER COLUMNS.

Designation	Name	Valve	Operation	Spout	Nozzle
I	Poage, style D	Globe	Manual	Telescopic	
II	Poage, style B	Globe	Manual	Rigid	Anti-splash
III	Poage, style F	Angle	Manual	Telescopic	
IV	Poage, style A	Angle	Manual	Rigid	Anti-splash
V	Otto	Angle	Manual	Ball & Socket	
VI	Gulland	Globe	Hydraulic	Rigid	Anti-splash
VII	Mansfield	Angle*	Manual	Rigid	With appended bucket
VIII	U. S.	Angle	Hydraulic	Rigid	With appended bucket
IX	Sheffield	Angle	Combination	Rigid	Conical anti-splash
X	Golden-Anderson	Globe	Hydraulic	Rigid	Anti-splash
XI	Sellew	Gate	Hydraulic	Rigid	Anti-splash
XII	Poage, style H	Angle	Manual	Telescopic	
XIII	Poage, style H	Angle	Manual	Rigid	Anti-splash
XIV	Otto	Angle	Manual	Telescopic	

*This angle valve does not replace the elbow.

5. *General Arrangement of Apparatus.*—In a test, the water column was connected to a tank or standpipe (hereinafter referred to as the tank) as shown in Fig. 1; a constant head was maintained in the tank during a test run by means of large pumps; the rate of discharge of the water column was measured by means

of a weir; and the pressures were determined by mercury gauges. The tank was 4 ft. in diameter and 60 ft. above the foundation and acted as a regulating chamber in maintaining a uniform flow. The pipe B leading from the 15 in. outlet of the tank was 12 in. in diameter. The nipple at C was connected with a 10 in. pipe 3 ft. long, and the water columns were connected to this 10-in. pipe at E. The piezometer connection at D was from 6 in. to 15 in. from the inlet E of the water column according to the form of connection with the water column. One opening was placed in the side of the 10-in. pipe and one in the bottom, cocks being arranged to permit readings to be taken from the separate openings. A ¾-in. pipe led from the piezometer connection to a mercury gauge placed in a convenient position. A second piezometer connection was made in the vertical part of the water column at a point G (Fig. 1) about 6 in. below the usual ground line and this was connected with a second mercury gauge. The point G was chosen where conditions would be fairly common in all the

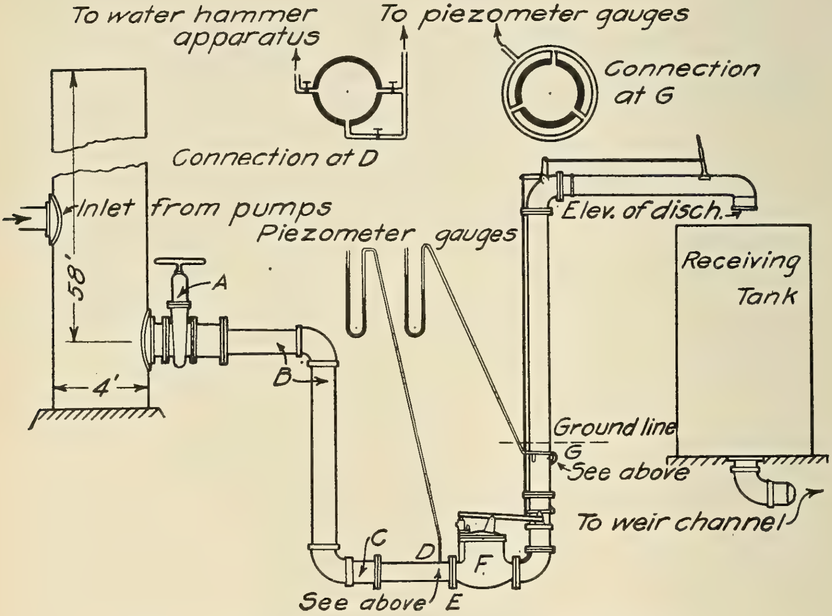

FIG. 1. GENERAL ARRANGEMENT OF APPARATUS.

water columns, being well above the valve arrangements in every case. The arrangement of the piezometer connection at D and at G is shown in the upper part of Fig. 1. The piping to the gauges was so arranged that any accumulating air would be carried out and the correct pressures observed. The effect of the elbows and the 10-in. connection was such that the distribution of flow over the section at D (Fig. 1) was not uniform, and this lack of uniformity may affect the piezometer readings noticeably for the higher flows, although observations taken alternately with the two piezometer openings at D showed only little differences. The difference in level between the zero level of these gauges and the discharge level of the water column was measured, and the pressure with reference to this discharge level was recorded. The level of the free discharge was considered as at the end of the spout, except that for the water columns with telescopic spouts (I, III, XII, and XIV), the center of the orifice discharging into the spout was used since there was free admission of air at this point. Having the observations and measurements, the total head lost in the column could be found. The observations also permitted the finding of the amount of head lost between the inlet to the column and the point in the riser just below the ground line; this would include the loss in the tee, the loss through the valve, and the frictional and other losses in the lower portion of the riser. The loss between the point below the ground line and the discharge outlet was also determinable. In all cases, of course, the head required to lift the water to the level of the spout was not counted as lost head. The discharge of the water column was measured over a 3-ft. standard weir having suppressed end contractions. This weir has been calibrated so that its coefficients are known with reasonable accuracy, and the conditions of the test were such that the measurement of the discharge is trustworthy.

6. *Procedure of Tests.*—For each of the water columns, tests were made in such a way as to give discharges of approximately, say, 1500, 2000, 2500, 3000, 3500, and 4000 gallons per minute, the head of water in the tank being made such as to produce the desired discharge. In starting the test the valve was opened under a low or medium head, and the water was maintained at a uniform height in the tank during the run. After the flow over the weir had become constant at about the desired discharge, readings of the pressure gauges and the hook gauge were taken

at four to five minute intervals for a period of twenty to thirty minutes. The pumps were then speeded up and the head in the tank increased until a quantity approximating the next higher discharge desired was obtained. After the flow over the weir had been found to be constant, readings were taken in a similar manner for a period of twenty to thirty minutes for the second run. Another increase in the head in the tank was then given and a run at the next higher discharge was made. The discharge was increased until it reached the limit of the capacity of the pumps for the head taken by the column under test. Repetitions were obtained to give a check on the general conditions of any test.

7. *Results of the Tests.*—The results of the tests are platted to logarithmic scale in Fig. 15, 17, ... 41 at the end of the text. The abscissas give the discharge in gallons per minute and the ordinates the head lost in feet of water. The values of the total head lost through the water column in the several experiments are shown by open circles. The values of the head lost through the part of the water column above the ground line piezometer connection are shown by solid circles. In each case the head necessary to give the velocity head and the entrance head are, of course, not included.

8. *Loss Diagrams.*—The lines for the 10-in. water columns drawn on Fig. 15, etc., agree very closely with the observed results. It would seem that this line may be used with fair accuracy up to a discharge of 5000 gal. per min. As drawn, the head lost is made to vary as the square of the velocity. It appears that the variation as the square of the velocity fits the results of all of the tests as closely as any power which could be selected.

From general considerations, it would seem reasonable to expect that 8-in. and 12-in. water columns will have losses approximately the same as those from the 10-in. water columns at the same velocity of flow, although, of course, the element of pipe friction through the column would probably differ somewhat from this, and result in a somewhat smaller loss for the 12-in. columns and a larger loss for the 8-in. water columns. The lines marked "8-in. water column, estimated", and "12-in. water column, estimated", are based on the assumption of equal losses at the same velocities. Some error is doubtless involved in this assumption, but these quantities may be found useful until more accurate information is available.

Curves representing the total loss in head for the various types of water columns are platted to natural scale in Fig. 2, page 10. Curves representing the loss in riser and spout are platted in Fig. 3, page 11.

9. *Tables.*—A comparison of the loss of head in the several water columns at equal discharges may be of interest.

Table 2 gives the loss of head in the 10-in. water columns for discharges of 3000, 4000, and 5000 gallons per minute. The column marked "Valve" in the table gives the loss from the inlet to the ground line, and, of course, includes other losses than valve losses. The column marked "Riser" gives the losses from the ground line up, including that in the spout in water columns having fixed spouts. For Table 2 and the succeeding tables, the values were taken from the lines of the diagrams.

TABLE 2.

LOSS OF HEAD IN 10-IN. WATER COLUMNS.

The loss is given in feet of water for the discharge indicated.

Designation	3000 gal. per min.			4000 gal. per min.			5000 gal. per min.		
	Valve	Riser	Total	Valve	Riser	Total	Valve	Riser	Total
I	12.6	2.9	15.5	22.5	5.2	27.7	35.0	8.0	43.0
II	12.6	5.1	17.7	22.5	9.0	31.5	35.0	14.0	49.0
III	11.3	2.9	14.2	20.3	5.3	25.3	31.3	8.0	39.3
IV	11.1	5.1	16.2	20.0	9.0	29.0	31.0	14.0	45.0
V	6.4	6.1	12.5	11.4	10.9	22.3	18.0	17.0	35.0
VI	16.3	7.2	23.5	29.0	12.8	41.8	45.0	20.0	65.0
VII	20.0	6.1	26.1	35.7	10.8	46.5	55.0	17.0	72.0
VIII	9.0	4.0	13.0	16.0	7.0	23.0	25.0	10.0	35.5
IX	6.4	6.7	13.1	11.3	12.0	23.3	17.8	18.7	36.5
X	13.5	6.8	20.3	24.4	12.0	36.4	37.5	19.0	56.5
XI	1.6	7.2	8.7	2.8	12.6	15.4	4.3	19.7	24.0
XII	6.1	2.8	8.9	10.9	4.9	15.8	17.0	7.6	24.6
XIII	6.2	5.7	12.1	11.1	10.0	21.1	17.3	15.7	33.0
XIV	6.5	2.4	8.9	11.5	4.3	15.8	17.8	6.8	24.6

Table 3 gives coefficients for the loss of head through the water column in terms of the velocity head $(\frac{v^2}{2g})$. If n represents this coefficient, the loss of head in feet equals $n\frac{v^2}{2g}$, v being the velocity in feet per second and g the acceleration of gravity. The nominal size of the column was used in calculating the velocity. The coefficients give a good means of comparing the losses in the

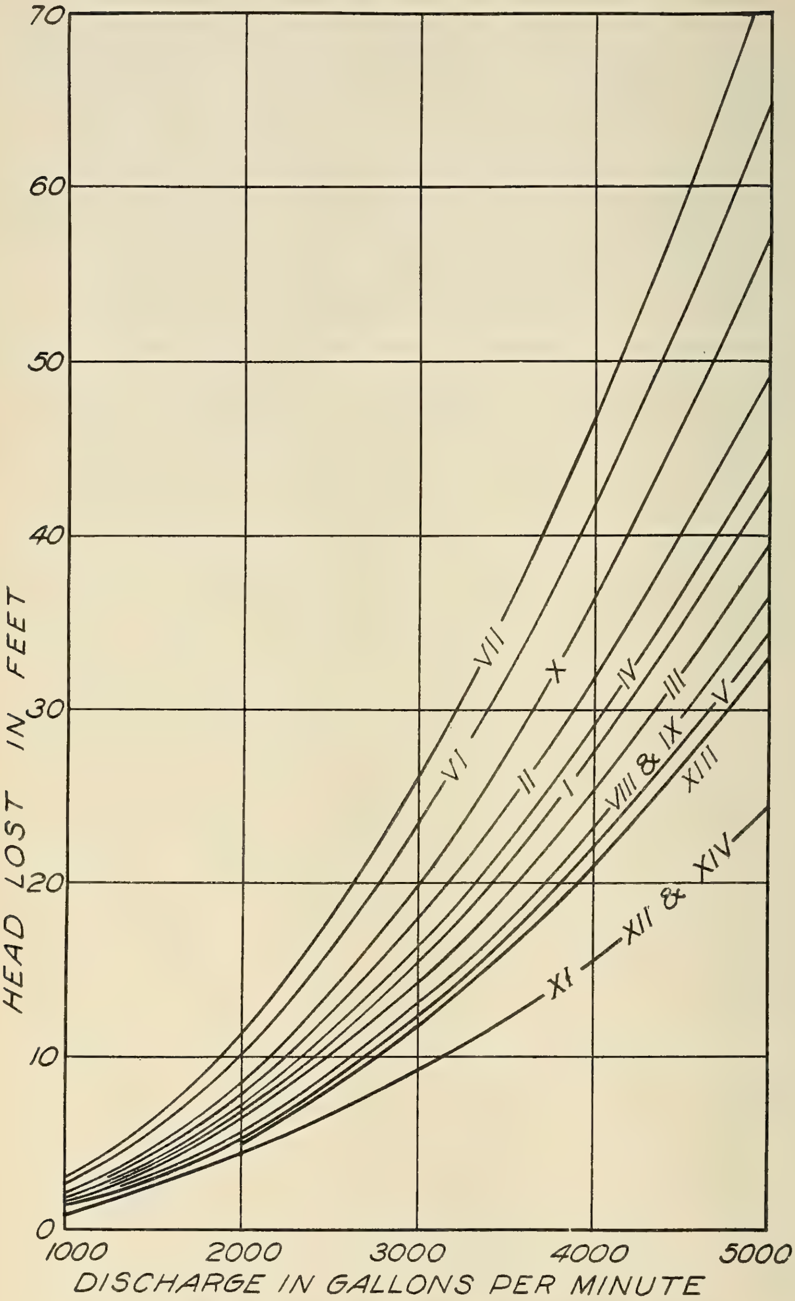

FIG. 2. LOSS OF HEAD IN WATER COLUMNS, ALL FORMS.

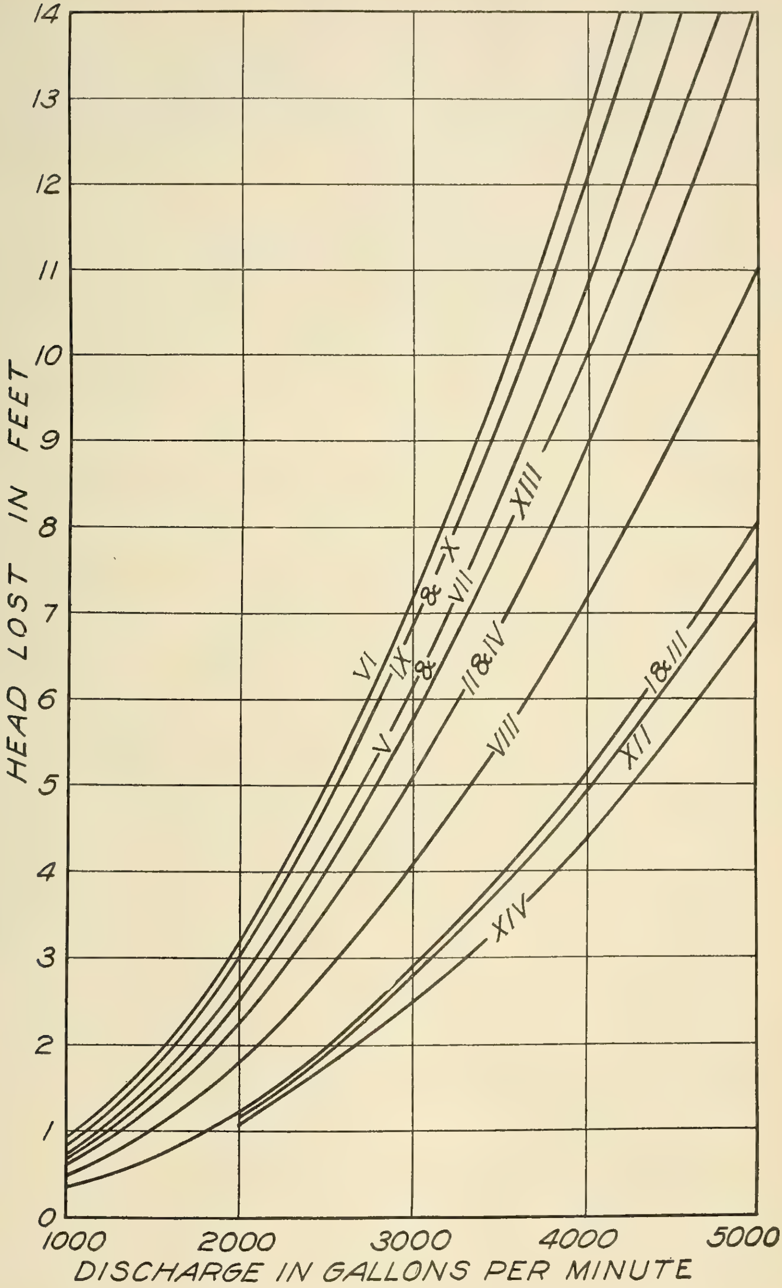

FIG 3. LOSS OF HEAD IN RISER AND SPOUT, ALL FORMS.

water columns with the losses by friction in supply pipe, bends, tees, etc. The table also gives the equivalent length of new cast-iron pipe which will give the same frictional loss as is found in the water column itself. As this length will vary somewhat with the velocity of flow, the tabular values are based on a discharge of 4000 gallons per minute.

TABLE 3.

COEFFICIENT OF LOSS OF HEAD IN 10-IN. WATER COLUMNS AND THE EQUIVALENT LENGTH OF STRAIGHT PIPE GIVING THE SAME FRICTION LOSS.

Designation	Coefficient n in $n\frac{v^2}{2g}$	Equivalent Length of Pipe		
		10-in.	12-in.	14-in.
I	6.72	338	791	1,690
II	7.65	384	900	1,920
III	6.14	308	722	1,540
IV	7.04	354	829	1,770
V	5.41	272	637	1,360
VI	10.20	510	1,195	2,550
VII	11.30	566	1,330	2,840
VIII	5.58	280	800	1.400
IX	5.65	284	811	1,420
X	8.83	444	1,040	2.220
XI	3.60	186	437	940
XII	3.67	190	446	960
XIII	4.94	256	603	1,295
XIV	3.67	190	446	960

TABLE 4.

LOSS OF HEAD IN 10-IN. WATER COLUMNS.

The velocities are given in feet per second and the loss of head in feet. These values may be considered also to be applicable to 8-in. and 12-in. water columns. The loss given does not include the velocity head of the entering water.

Designation	Loss of Head for Velocity Given in Caption			
	10	12	15	20
I	10.3	14.6	23.2	41.4
II	11.7	16.9	26.4	47.0
III	9.4	13.5	21.2	37.6
IV	10.8	15.5	24.2	43.1
V	8.3	12.0	18.7	33.5
VI	15.6	22.5	35.1	62.4
VII	17.3	25.0	39.0	69.3
VIII	8.6	12.3	19.3	34.3
IX	8.7	12.5	19.6	34.8
X	13.5	19.5	30.4	54.0
XI	5.6	8.0	12.6	22.4
XII	5.7	8.2	12.9	22.8
XIII	7.7	11.1	17.3	30.7
XIV	5.7	8.2	12.9	22.8

Table 4 gives the loss of head in 10-in. water columns for four velocities. It may be considered to be applicable within fair limits of accuracy to 8-in. and 12 in. water columns.

Table 5 gives losses for given discharges through 8-in., 10-in., and 12-in. water columns. These tables will be convenient for comparison.

TABLE 5.

Loss of Head in Water Columns.

This table is based on the loss found in 10-in. columns and on the assumption that the loss of head at any given velocity of water is the same for the different sizes of columns of a given type. The loss is given in feet of head of water and the discharge in gallons per minute.

Designation	8-in.		10-in.		12-in.	
	2,000	2,500	3,000	4,000	4,500	6,000
I	16.7	26.0	15.5	27.7	16.7	30.0
II	19.0	30.0	17.7	31.5	19.0	24.0
III	15.6	24.6	14.2	25.3	15.6	28.2
IV	17.3	27.0	16.2	29.0	17.3	31.0
V	13.5	21.0	12.5	22.3	13.5	24.0
VI	25.1	39.5	23.5	41.8	25.1	45.0
VII	28.0	43.0	26.1	46.5	28.0	50.0
VIII	14.0	22.0	13.0	23.0	14.0	25.0
IX	14.1	22.2	13.1	23.3	14.1	25.5
X	22.0	24.5	20.3	36.4	22.0	39.5
XI	9.5	14.6	8.7	15.4	9.2	16.7
XII	9.7	14.9	8.9	15.8	9.6	17.0
XIII	13.2	20.5	12.1	21.1	13.0	22.4
XIV	9.6	14.9	8.9	15.8	9.6	17.0

10. *Comments on Loss of Head.*—By examining the water columns it may be seen that the form of some of them is not in accordance with the principles of good hydraulic design. Sudden changes in direction, sudden contraction and expansion of the section of the stream, and tortuous passages are among the objections found, and high local velocities are especially troublesome. The high losses found in some of the water columns were, therefore, not unexpected. It seems probable that the need of providing certain mechanical features was placed uppermost in making the design, and that the hydraulic requirements were neglected. Some of the columns which have excellent mechanical features give high hydraulic losses. It goes without saying that both hydraulic and mechanical features are important matters in the design of a water column. As an illustration of modifications in design which will give improved hydraulic conditions without loss

in mechanical advantages, water columns XII and XIII may be cited, as compared with water columns III and IV.

It is evident that the rate of discharge of water columns under working conditions is much less than many engineers have supposed and that water columns are frequently rated too high in the catalogs of manufacturers. To put it the other way, the loss of head for a given discharge is considerably higher than it has been estimated to be, and probably higher than is necessary. A comparison with the length of pipe which will give a friction loss equal to the loss through a 10-in. water column may help to give an appreciation of the great loss of head in the water column. It may be shown that at a given discharge the loss through a 10-in. water column is equal to the frictional loss for the same discharge through a 10-in. pipe line 186 ft. long with the water column having the lowest loss of any in the series except XI, and 566 ft. long with the one having highest loss; or if a 12-in. pipe be used to feed the 10-in. water column a line 437 ft. long would give the same friction loss as the first-named water column, and one 1330 ft. long the same as the last-named water column. If it is necessary to lift the water to a greater elevation to provide the necessary head, it is evident that the cost of pumping water to the extra height and also the expense of giving a greater elevation to the tanks must be considerable. Or, to view it from another point, the rate of discharge for ordinary elevations of supply tank will be much smaller than is generally expected, and smaller than may be obtained with more efficient water columns. The use of larger water columns suggests itself as one way of keeping the lost head to a reasonable limit, though it is reported that firemen have some difficulty in handling some types of adjustable spouts of the larger columns.

Another indication of the large loss through water columns is seen in the large values of the coefficient n given in Table 3. A comparison with the coefficients for the loss of head in bends and valves brings this out in a striking manner.

11. *The Discharging Capacity of Water Columns.*—Since the head available in a water column depends upon local and other conditions, and the economic problem is so varied, the selection of a limiting or maximum velocity of flow upon which general design may be based can not be made. However, it is evident that the economical velocity through a water column and also through

the supply main will be much above the limiting velocity used in ordinary water-works practice where continuous flow throughout twenty-four hours and the cost of pumping against the friction head of long lines of mains combine to make the economical velocity less than 5 ft. per second and sometimes as low as 3 ft. per second. Aside from such considerations as the cost of pumping and that of giving sufficient elevation to the supply tanks, the maximum velocity allowable through a water column will depend upon such matters as the satisfactory operation of valve and the effect of closing the valve in producing water hammer in the supply main. From a study of these tests and a comparison with water-works practice, it would seem that with a short line of pipe from the supply tank a velocity of 12 or 15 ft. per second through the water column may be considered as the maximum desirable velocity for ordinary conditions, and for longer lines the limiting velocity should be smaller. For a long line of supply main the limit of allowable velocity would be perhaps as low as 8 ft. per second. It would seem, then, that 3000 gal. per min. for an 8-in. water column, 4000 gal. per min. for a 10-in. water column, and 6000 gal. per min. for a 12-in. water column may perhaps be considered to be the limit of desirable flow through water columns. It would also appear that a loss of much more than 20 ft. of head for the discharges just mentioned may be considered to be excessive, under conditions of ordinary tank supply.

12. *Calculations for Water Service Installation.*—Although the calculations involved in the design of sizes for water service plants are not within the scope of this bulletin, it may be convenient to some readers to include here a brief review of a method which may be used in making calculations of sizes of pipe mains and loss of head. The method here given follows the report of the Committee on Water Service of the American Railway Engineering and Maintenance of Way Association*, the method being the joint work of Mr. Ferriday and the writers.

The total head producing flow (called by the Committee the "flow head") is utilized in overcoming resistances and is equivalent to the sum of several items,—velocity head of the flowing water, loss at entrance, friction in pipe, loss in elbows, etc., and loss through the water column. This may be expressed by the following equation:

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* See the Proceedings of the American Railway Engineering and Maintenance of Way Association, vol. 11, p. 1161.

$$H = m\frac{v^2}{2g} + e\frac{v^2}{2g} + h_1 + n\frac{v^2}{2g} + \frac{v^2}{2g} \dots\dots\dots\dots\dots\dots \quad (1)$$

where H is the "flow head", $m\frac{v^2}{2v}$, $e\frac{v^2}{2g}$ and $n\frac{v^2}{2g}$ are the losses in head at entrance, in elbows and tees, and in the water column, respectively, $\frac{v^2}{2g}$ is the velocity head of the issuing water, and h_1 is the frictional loss in the pipe line. The values h_1 and the losses in elbows and tees may be obtained from the diagrams in Fig. 11, 12, and 13, which are explained in the Appendix. For these diagrams the units are feet and seconds. When the supply main and the water column are not of the same diameter, the v to be used in the several terms will be that for the size in which the loss occurs.

If it is desired to know the flow head necessary to produce a given discharge, substitute values in equation (1). Thus, if 6000 gal. per min. is to be discharged through 200 ft. of 14 in. pipe and there is one elbow with a radius of curvature equal to 1½ diameters and if the water column used is a 12-in., Type V, the following values of the heads will be obtained, if we neglect loss in contraction of section from 14-in. pipe to 12-in. column:

	Feet of head.
Entrance head $m\frac{v^2}{2g}$ (Fig. 13, $m = 1$)	2.5
Loss in one elbow $e\frac{v^2}{2g}$ (Fig. 13)	1.1
Loss in 200 ft. of 14-in. pipe, (Fig. 12)	6.6
Loss in water column (Fig. 23)	24.0
Velocity head $\frac{v^2}{2g}$ (Fig. 13)	4.5
	38.7

That is, it will require that the level of water in the supply tank remain not less than 38.7 ft. above the level of the discharge point of the water column.

If a given combination of pipe line and water column and a specified flow head be the known quantities and it is desired to find the rate of discharge, the most convenient process is a trial method. Assume a discharge as close to the probable discharge as may be estimated and by equation (1) calculate the flow head required to give this discharge with the combination of pipe line and water column. Divide the specified flow head by the flow head thus found by calculation and call the quotient the trial ratio. Multiply the water column loss used in the calculation by this ratio; the product may be considered an approximation to the loss which will be found in the water column under the conditions specified. From the diagram for water column losses find the discharge which corresponds to this water column loss. The amount so found will be approximately the discharge of the given combination of pipe line and water column. As a check, the head required to give this discharge may be computed by equation (1), and if the result is not close enough the steps indicated may be gone through again, using as a new trial ratio the quotient of the specified flow head by the flow head obtained by this calculation. The result of the first calculation will usually be within the required degree of accuracy.

As an example, let it be required to find the discharge through 400 ft. of 12-in. pipe and a 10-in. water column of Type VIII, the line having two elbows with radius of curvature of 1½ diameters and the controlling level of the water in the tank being 30 ft. above the discharge orifice of the water column. Assume that the discharge will be 3000 gal. per minute. Then the necessary head by equation (1) may be found as follows:

	Feet of head
Entrance head, $m\frac{v^2}{2g}$ (Fig. 13, $m = 1$)	1.1
Loss in two elbows, $e\frac{v^2}{2g}$ (Fig. 13)	1.0
Loss in 400 ft. of 12-in. pipe (Fig. 12)	8.4
Loss in water column (Fig. 29)	13.0
Velocity head (10-in.) (Fig. 13)	2.5
Total head required,	26.0

The trial ratio then is $\frac{30}{26} = 1.15$, and the loss through the water column may be expected to be $13.0 \times 1.15 = 15.0$ ft. By Fig. 29, the discharge through the water column for a loss of head of 15 ft. is 3250 gal. per min. Using equation (1) for a discharge of

3250 gal. per min., the calculated loss is found to be 29.9 ft., so that the discharge of 3250 gal. per min. may be considered to be sufficiently close.

Table 6 gives examples of combinations of pipe lines and water columns under assumed conditions of height of tank and flow head, length of pipe line, and kind of water column, with summarized results of calculations of the discharge and the distribution of the flow head among pipe friction, loss in water column, etc.

TABLE 6.

EXAMPLES SHOWING THE DISCHARGE AND THE LOSSES FOR VARIOUS COMBINATIONS OF PIPE LINES AND WATER COLUMNS.

Distances, heads and losses are given in feet; diameters in inches; discharges in gallons per minute.

Depth in Tank	Tank Bottom above Rail.	Pipe Line		Water Column		Discharge	Entrance Loss	Velocity Head	Elbow Loss	Pipe Friction	Column Loss	Total
		Length	Diam	Dia.	Des.							
16.0	20.0	1000	12	10	V	2 370	0.7	1.5	0.5	13.5	7.8	24.0
5.0	20.0	1000	12	10	V	1 700	0.3	0.7	0.4	7.6	4.0	13.0
16.0	20.0	1000	14	10	V	2 880	0.6	2.3	0.5	9.1	11.5	24.0
5.0	20.0	1000	14	10	V	2 110	0.4	1.1	0.3	5.1	6.2	13.0
16.0	20.0	1000	12	12	V	2 690	0.8	0.8	0.7	17.0	4.7	24.0
16.0	20.0	1000	14	12	V	3 500	0.9	1.5	0.8	12.8	8.0	24.0
16.0	20.0	1000	16	12	V	3 950	0.6	1.8	0.6	8.7	10.4	24.0
5.0	20.0	1000	16	12	V	2 950	0.4	1.2	0.3	5.2	5.9	13.0
16.0	20.0	1000	14	10	XII	3 070	0.8	2.5	0.5	10.0	9.3	23.2
16.0	20.0	1000	14	10	VI	2 410	0.5	1.6	0.4	6.5	15.0	24.0
16.0	20.0	500	10	10	XII	2 250	1.4	1.4	1.3	14.1	5.0	23.2
16.0	20.0	500	12	10	XII	2 950	1.1	2.3	0.8	10.3	8.7	23.2
16.0	20.0	500	14	10	XII	3 490	0.7	2.8	0.7	6.4	12.0	23.2
16.0	20.0	500	14	10	VI	2 580	0.5	1.9	0.5	3.7	17.4	24.0
16.0	20.0	200	10	10	XII	2 830	2.2	2.2	2.0	8.8	8.0	23.2
16.0	20.0	200	12	10	XII	3 450	1.4	2.4	1.3	5.4	11.7	23.2
16.0	20.0	200	14	10	XII	3 800	1.0	3.8	0.9	3.0	14.4	23.2
16.0	20.0	200	14	10	VI	2 720	0.6	2.0	0.5	1.7	19.2	24.0
16.0	20.0	100	10	10	XII	3 160	2.4	2.7	2.8	5.4	9.9	23.2
16.0	20.0	100	12	10	XII	3 690	1.8	3.5	1.5	3.0	13.4	23.2
16.0	20.0	100	14	10	XII	3 910	1.1	4.1	1.1	1.6	15.3	23.2
16.0	32.0	1000	14	10	V	3 560	1.0	3.4	0.8	13.2	17.6	36.0
16.0	32.0	500	14	10	XII	4 300	1.4	5.0	1.1	9.3	18.4	35.2
16.0	32.0	200	12	10	XII	4 280	2.3	4.8	2.1	7.8	18.2	35.2
16.0	32.0	100	12	10	XII	4 520	2.7	5.4	2.3	4.4	20.4	35.2
16.0	32.0	100	14	10	XII	4 870	1.6	6.2	1.5	2.3	23.6	35.2
16.0	32.0	100	14	10	VII	3 160	0.8	2.7	2.4	1.1	29.0	36.0
16.0	32.0	100	14	12	XII	6 500	2.9	5.5	2.6	4.9	20.2	35.2

13. *Principles of Water Hammer Caused by Sudden Stoppage of Flow.**—When a valve at the end of the pipe line is suddenly closed, additional water pressure is produced throughout the pipe line. Some of the conditions and results attending the phenomena may be briefly stated as follows:

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* A bulletin of the Engineering Experiment Station on Water Hammer in Pipes is in preparation and will treat more fully the matters referred to in this article.

(1) The energy of the moving water is expended in compressing the water in the pipe and in expanding the walls of the pipe.

(2) An increased pressure is developed within the pipe, and the increase of pressure is called water hammer.

(3) The water next to the valve is immediately stopped and the full amount of water hammer is developed instantly at that point, the term "instantly" being here used to mean a very short time.

(4) The amount of this water hammer in pounds per square inch in pipes of the size and kind here considered is about fifty-four times as much as the original velocity of the water in feet per second.

(5) The water in the pipe away from the valve is stopped and compressed layer by layer, the full amount of the water hammer developing almost instantly at any point as soon as the water between that point and the valve has received its compression.

(6) This pressure wave or impulse of the water hammer (and the time when each layer receives its compression) moves along the pipe line away from the valve with a speed of about 4000 ft. per sec. for the size of pipe ordinarily used in supply mains. The rate of travel is the same as the velocity of sound in water as modified by the thickness and elasticity of the walls of the pipe.

(7) When a pressure wave has traveled to a free water surface or to a larger body of water, a release of pressure begins at this relief point and travels backward at the same speed, about 4000 ft. per sec. The water at any point in the pipe is held at its full water hammer pressure while this impulse or pressure wave travels on to the point of release and back. At the valve the pressure will last the longest. Thus for a pipe 2000 ft. long, the water hammer pressure at the valve will be maintained for one second.

(8) This first pressure or first pulsation of pressure is followed by a series of pulsations of diminishing intensity. The water in the pipe may be considered as a springy substance bounding and rebounding from the closed end.

(9) The pressure developed when closure is sudden, is expressed by the formula, the derivation of which will not be given here:

$$P = \frac{1}{\sqrt{1 + \frac{Ed}{E't}}} \sqrt{\frac{wE}{144g}}\, v \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2).$$

in which

P = water hammer pressure (lb. per sq. in.), the maximum additional pressure for a given velocity of flow.

v = the velocity of the water in the pipe before valve was closed (ft. per sec.)

E = modulus of elasticity of the water (300 000 lb. per sq. in.)

E' = modulus of elasticity of the metal in pipe (30 000 000 lb. per sq. in. for steel and 15 000 000 lb. per sq. in. for cast iron.)

d = diameter of pipe.

t = thickness of pipe wall.

g = acceleration of gravity (32.2 ft. per sec. per sec.)

w = weight of a cubic unit of water (62.5 lb. per cu. ft.)

For cast-iron pipe of the sizes used as supply lines the formula reduces to approximately

$$P = 54\, v \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3).$$

(10) By sudden closing of the valve is meant that the effective part of the closure takes place in less than the time required for the first impulse to travel to the tank and back to the valve at a rate of approximately 4000 ft. per sec. This velocity (V) of the pressure wave is given by the formula

$$V = \frac{4710}{\sqrt{1 + \frac{Ed}{E't}}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4).$$

The effective part of the closure begins when the resistance through the valve opening becomes large enough to give a considerable check to the flow of water. For the water columns under consideration, the effective part of the closure may be said to be the last 15 % to 25 % of the valve movement.

(11) The length of the pipe line does not enter into the expression for the amount of water hammer developed by sudden closure of the valve. It does affect the length of the time the water is under compression and hence in a way the damage which may be done. The length of pipe line is of importance in the problem in that if the valve is closed in a shorter length of time than is necessary for the wave to travel out and back, the resulting water hammer is the same as that which would be obtained with instantaneous closing of the valve. The pressure produced when the valve closure is slow is discussed in a later paragraph.

14. *The Effect of Valve Movement Upon Pressure.*—The following theoretical investigation will assist in obtaining an idea of what is taking place in the supply line after the valve is closed, first for the case of slow closure, and second for the case of sudden closure. In a long line of pipe when steady flow has become established,

$$H = m\frac{v^2}{2g} + f\frac{l}{d}\,\frac{v^2}{2g} + e\,\frac{v^2}{2g} + n\,\frac{v^2}{2g} + q\,\frac{v^2}{2g} + \frac{v^2}{2g} \quad \ldots\ldots\ldots\ldots(5)$$

$$= [\,(m + f\frac{l}{d} + e + n + 1) + q]\,\frac{v^2}{2g} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(6)$$

in which q is the coefficient of valve loss, a variable whose value depends upon the amount the valve is closed; $m\frac{v^2}{2g}$ is entrance loss, $f\frac{l}{d}\,\frac{v^2}{2g}$ the loss in pipe friction, $e\frac{v^2}{2g}$ the loss in elbows, $n\frac{v^2}{2g}$ the column loss and $\frac{v^2}{2g}$ the velocity head. For simplicity place

$$m + f\frac{l}{d} + e + n + 1 = a$$

Then

$$H = (a + q)\,\frac{v^2}{2g}$$

and

$$v = \sqrt{\frac{2gH}{a + q}} \quad \ldots\ldots\ldots\ldots\ldots\ldots(7)$$

It will be noticed that the velocity of flow produced by the head H depends upon both a and q. As an illustration, it has been found that for a gate valve 82 % closed $q = 41$. Then if

$a =$ 13.7, the velocity in the pipe after steady flow has become established will be $\frac{1}{2}$ of the velocity in the pipe when the valve is open; if

$a =$ 53.0, the velocity will be $\frac{3}{4}$ of that with valve open; if

$a =$ 175.6, the velocity will be $\frac{9}{10}$ of that with valve open.

These values show that the velocity of flow is affected but little in a long pipe during the first 80 % of the closing of the valve, the three values of a corresponding to lengths of 12-in. pipe of 685 ft., 2660 ft., and 8800 ft., respectively. In Fig. 4 have been plotted the results of calculations with equation (7), using Weisbach's values of q for gate valves and five values of a. The curves show how the velocity in the pipe diminishes as a very slow closure of valve is made, the total head remaining constant. To use the diagram, the value of a for the pipe line should be computed. As an illustration, for a 12-inch pipe line 500 ft. long, with four elbows and with a 10-inch water column, a equals 12.4, and the values may be interpolated between the lines a = 10 and a = 20. It should

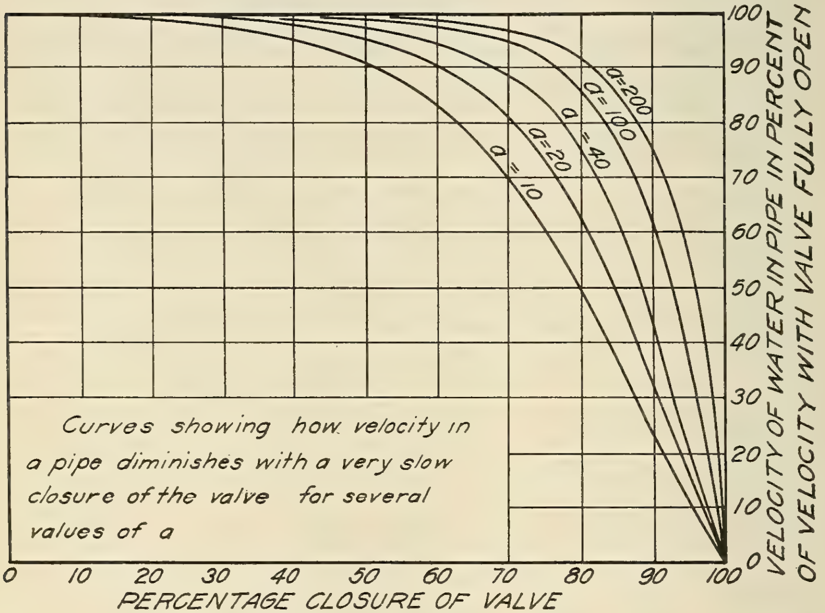


FIG. 4. DIAGRAM SHOWING THE VELOCITY IN PIPE LINES OF VARIOUS LENGTHS FOR ANY VALVE POSITION,—STEADY FLOW CONDITIONS.

be noted that a should be computed using a velocity head based upon a diameter of pipe equal to the size of the pipe line.

When the valve is closed quickly, equation (7) does not apply because a water hammer pressure is produced which forces the water past the valve and hence keeps the velocity in the pipe at a higher value than it would have during a very gradual closure. If the valve is closed in less time than $\frac{2l}{4000}$ seconds, it may be considered a sudden closure, and the velocity in the pipe near the valve at any valve position can be computed as follows. During a partial closure, the value of the valve coefficient q has changed from q_1 to q_2, and the head or resistance at the valve (neglecting the back pressure from the water column itself) is now

$$P = q_2 \frac{v^2}{2g} \ldots\ldots\ldots\ldots (8)$$

Call the velocity v_s after the flow has become steady. The pressure at the valve at that time becomes

$$P_s = q_2 \frac{v^2_s}{2g} \ldots\ldots\ldots\ldots (9)$$

v_s can be computed from equation (7) when q_2 is known, whatever the position of the valve.

From equations (8) and (9)

$$v = v_s \sqrt{\frac{P}{P_s}} \ldots\ldots\ldots\ldots (10)$$

If the velocity was originally v_o the water hammer generated would be

$$P = 54\,(v_o - v) \ldots\ldots\ldots\ldots (11)$$

Substituting for P in equation (10),

$$v^2 = \frac{54\,v^2_s}{P_s}\,(v_o - v)$$

or

$$v = -\frac{54\,v_s^2}{P_s} + \sqrt{\frac{54 v_s^2 v_o}{P_s} + \left[\frac{54 v_s^2}{P_s}\right]^2} \ldots\ldots\ldots\ldots (12)$$

Knowing v, P can be found from equation (8).

If the values of q are known for any valve, the manner of increase of pressure during a rapid closing of the valve can be easily determined. In Fig. 5 have been plotted the results of calculations with equations (8) and (12) using Weisbach's values of q for gate valves. The curve shows the way in which the velocity of the water in the pipe near the valve diminishes during a sudden closure of the valve. Note that the velocity is 80 per cent of its original value when valve is 90 per cent closed.

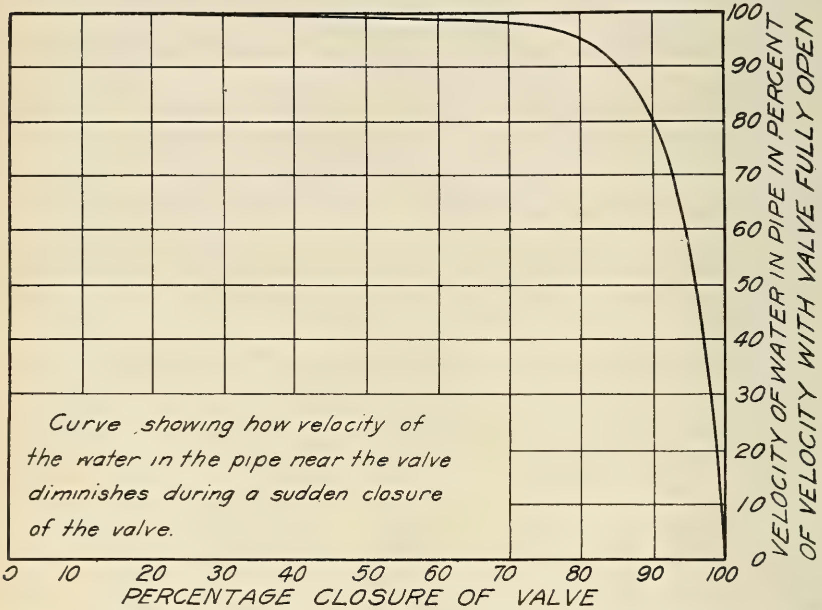


Fig. 5. Diagram Showing Velocity in a Pipe Line for Any Valve Position during a Sudden Closure of Valve.

In Fig. 6 are curves worked out with equations (7) and (8) for pipe of various lengths. These curves show the amount of pressure or resistance developed during a very slow closure of a gate valve for different values of a. Note that for very long pipe lines, the pressure against the valve (resistance of valve opening) does not become any considerable proportion of the total flow head until the valve is more than 90 per cent closed. In short pipe lines, closure of the valve is felt much earlier, as is seen in the curves for the smaller values of a.

Fig. 7 shows how the pressure would rise in a pipe of any length if the valve is closed suddenly. The length of pipe need not be considered because it does not enter into equations (8) and (12).

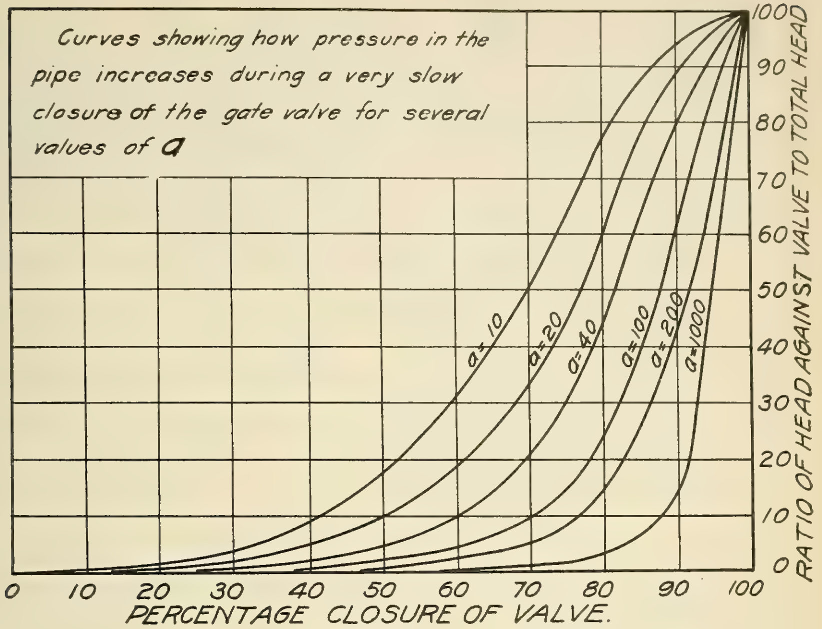


FIG. 6. DIAGRAM SHOWING PRESSURE ON GATE VALVE AT END OF PIPE LINE FOR ANY VALVE POSITION, AND FOR VARIOUS LENGTHS OF PIPE—STEADY FLOW CONDITIONS.

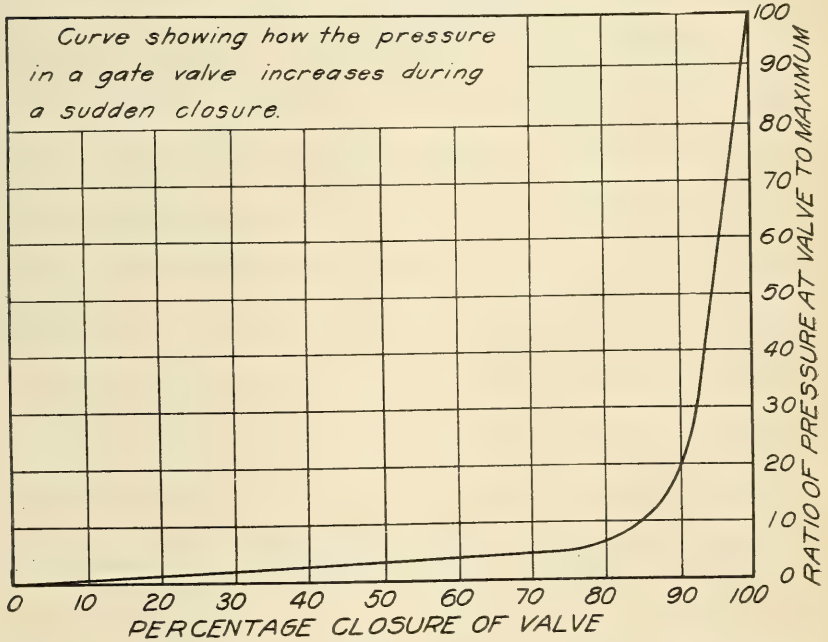


FIG. 7. DIAGRAM SHOWING PRESSURE ON GATE VALVE AT END OF PIPE LINE FOR ANY VALVE POSITION DURING A SUDDEN CLOSURE.

15. *Time-pressure and Valve-movement-pressure, Diagrams.*—The valve A (Fig. 1, page 6) was partially closed, so as to give added resistance to flow in the pipe line. As valve E closes it consumes more and more of the pressure until the entire static pressure is taken. Observations were first made with valve A slightly closed. The valve A was then closed somewhat more and another experiment made. The pressure at C was recorded by a Crosby indicator in two ways: (1) on a drum rotating at a uniform rate, (2) with the drum connected by a cord to the valve mechanism and moving as the valve moved. An electric attachment recorded half seconds on both forms of diagram. Fig. 8 and 9 (page 28 and 29) give the results of the tests made in this way. The diagrams are here called (1) time-pressure diagrams and (2) valve-movement-pressure diagrams, respectively.

Under the conditions of flow

$$H = b\frac{v^2}{2g} + q\frac{v^2}{2g}$$

where $b\frac{v^2}{2g}$ represents all losses except that due to the water column valve. Hence

$$v = \sqrt{\frac{2gH}{b+q}} \qquad \text{(13)}$$

which is similar to equation (7).

By means of the valve A any value of b can be obtained, and as b is similar to a in equation (7), a diagram can be produced which will represent the manner in which pressure rises in any pipe line. The valve-movement-pressure diagrams are similar to the curves in Fig. 6 (page 25). It will be noted from Fig. 6 that there is not much change in the shape of the pressure curve when a is greater than, say, 40. It was not possible to obtain this form of diagram from some of the hydraulically operated valves because the moving parts are not accessible. It will be noticed on diagrams of water columns I, II, III, IV, V, and XIV, shown in Fig. 9, that the rise does not begin until the valve is nearly 95 per cent closed. From Fig. 6 it is seen that with a gate valve in a pipe line which has a even as high as 1000 the pressure begins to rise at 90 per cent closure. The difference can be explained by the construction of the valves. A cylinder valve closes off a much larger fraction of total area in the last 10 per cent of the closure than does a gate valve. In column VII it is seen that the pressure begins to rise at 40 per cent of the closure. This was caused, at least in part, by the very short valve travel. The travel in this case was so short that some of the great loss of head for this column must be attributed to the smallness of the opening.

The time-pressure diagrams were obtained for all the water columns and are shown in Fig. 8. A study of these shows that except in water columns XII and XIII a very short time is used for what may be called the effective portion of closure—that is the portion of the closure which produces the principal retardation of the water in the pipe. Columns I and II use 17 seconds for closing, and the effective portion of closure occupies only a little more than one second. With a pipe line 2000 feet long or more, great water hammer pressures would be produced unless prevented by a relief valve. Columns XII and XIII have the first portion of the closure made very rapidly, and the last or the effective portion of the closure is made very slowly. It may be seen from Fig. 9 that in one experiment with columns XII and XIII the first 83% of the closure was made in 2 sec., and the rest of the closure was made in 11 sec. In its effect upon water hammer this is the same as closing the valve at a uniform rate in 65 sec. instead of in the 13 sec. which was actually used; columns III, IV, V, IX, and X make the effective portion of closure in about ½ second. A supply line 1000 feet long would be liable to have destructive water hammer unless protected by relief valves. Columns VI and VIII are hydraulically operated, and both show that the closure is hastened by an increased pressure in the supply line. Column VI has 3 seconds for the shortest effective portion of closure shown on diagram. Triangular ports are the reason in this case for the comparatively long time of effective closure. The valve must move a relatively large amount near the end of the closure to cover up a given area of port. A disadvantage of the triangular port may be seen by a comparison of the loss of head with column X which is similar in almost every respect but has rectangular ports. At 4000 gal. per min. 29 feet of head are lost in the valve of column VI against 24.4 feet in valve of column X.

16. *Application to Formation of Water Hammer in Supply Lines.*—The supply line used in the experiments was too short to permit water hammer to be developed to any extent. The time-

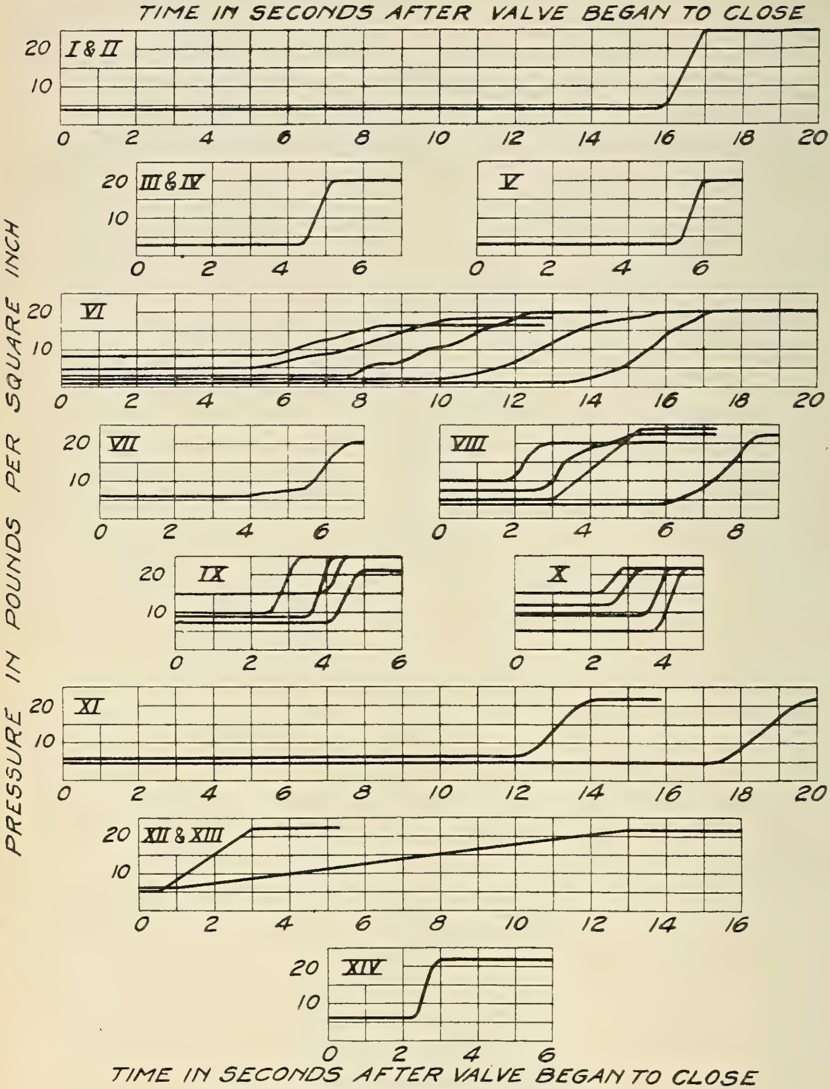


FIG. 8. TIME-PRESSURE DIAGRAMS.

pressure and valve-movement-pressure diagrams give information from which the formation of water hammer in supply lines may be forecast.

(1). Velocities as high as 15 ft. per sec. in the supply line of a water column are not uncommon, while a velocity as high as 10 ft. per sec. is quite usual. With such large quantities of water flowing it is necessary that the water column be shut off promptly when the locomotive tender is full. The time required in closing the valves experimented upon ranged from 3 to 17 seconds, most of the valves closing in less than 8 seconds. The high velocity and the short time of closure make destructive water hammer possible unless means are used to prevent it. With a velocity of 10 ft. per sec. in the supply line, 540 lb. per sq. in. water hammer is possible.

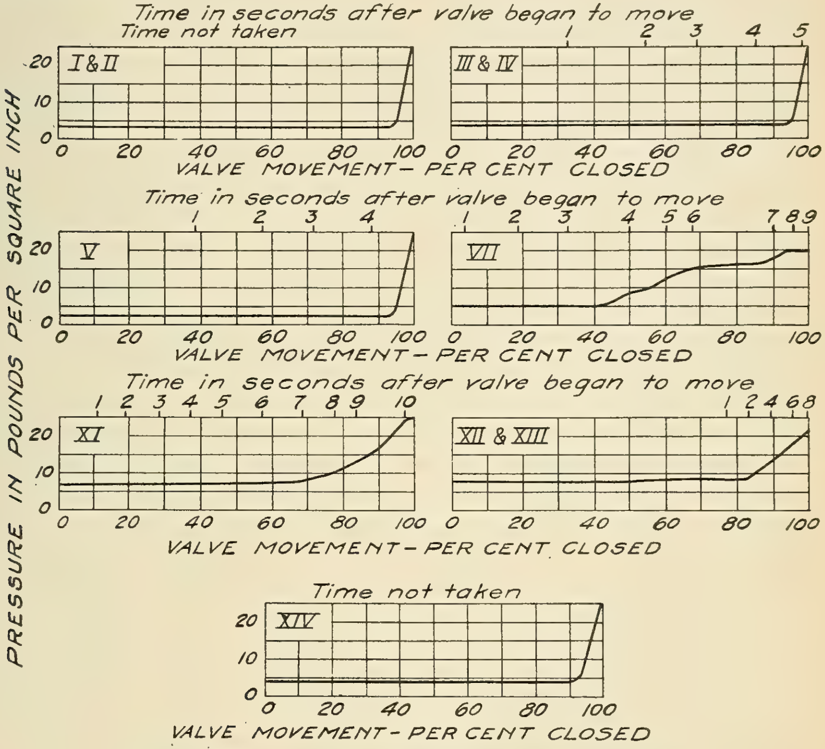


FIG. 9. VALVE-MOVEMENT-PRESSURE DIAGRAMS.

(2). From an examination of the time-pressure and valve-movement-pressure diagrams (Fig. 8 and 9) it will be noted in almost all the makes that the pressure does not begin to rise rapidly until the valve is about ninety per cent closed and until only a very short time remains before valve is completely closed. Water column VII (Mansfield) is an exception. The remaining part of the closure is the effective portion of closure.

(3). If the time in seconds taken by the effective portion of the closure is equal to or less than twice the length of the supply line in feet divided by 4000, maximum water hammer will be caused. If there is no relief valve or other device for reducing the water hammer, the pressure in pounds per square inch will be approximately 54 times the velocity of the water in feet per second in the supply line before shutting valve.

(4). If the time in seconds taken by the effective portion of the closure is greater than twice the length of the supply line in feet divided by 4000, maximum water hammer will not be caused. The magnitude of the pressure will depend upon the manner in which the last part of the closure is made.

(5). It is immaterial how quickly the first eighty per cent or so of the closure is made. By making this part of the closure in less time, the time saved can be used in making the last part of the closure more gradual. For example, assume that a valve is closed at a uniform rate in 10 sec. Reducing the time of making eighty per cent of the closure to 4 sec. and making the last twenty per cent of the closure in 6 sec. keep the total time of closure at 10 sec., but its effect on water hammer is the same as if a uniform closure were made in 30 sec.

This statement which was formulated before the later tests were made is well exemplified in an experiment with water column XII in which the first 83% of closure was made in 2 sec., and the last 17% of closure in 11 sec. (See Fig. 8 and 9, page 28 and 29.)

17. *Pressures Produced by Slow Closure of Valve.*—In some of the preceding paragraphs the water hammer produced by sudden closure of valve was discussed. When the time taken to make the effective part of the valve closure is greater than the time required for the pressure wave to make a circuit out and back, the amount of water hammer will be less than given by the formula for maximum water hammer. In case the time taken for closure becomes so much greater that the pressure at the valve is hardly more than the resistance which the partially closed valve gives to the passage of the amount of water carried at a given instant (and hence no real water hammer is produced or so little that it need not be considered), the problem is of a quite different nature. The following method for determining the effect of slow closure may be used.

From the principle of impulse and momentum,

$$\int_{t'}^{t} Pdt = \int_{v'}^{v} \frac{62.5\ l}{32.2\text{x}144} dv \ldots\ldots\ldots\ldots\ldots (14)$$

where

$P =$ resultant pressure in lb. per sq. in. at any instant.
$t =$ time in seconds.
$v =$ velocity in pipe in ft. per sec. at any instant.
$l =$ length of pipe in feet.

For very short intervals of time and small changes of velocity, the approximate form may be used:

$$P\,(t - t') = 0.0135\ l\,(v - v') \ldots\ldots\ldots\ldots\ldots (15)$$

If the law of the valve movement and the corresponding valve resistance during closure are known, (that is, if the time-pressure diagram and the valve-movement-pressure are given, or if the coefficients of valve resistance and the law of valve closure are known), the pressures produced during slow closure may be calculated approximately by the use of equations (8) and (15). As an illustration, the additional pressures developed in a 10-in. pipe line 1000 ft. long with flow head of 45 ft. have been calculated, by an equation not given here, for a cylindrical valve for various times of closing at a uniform rate and plotted in Fig. 10. If the valve does not close at a uniform rate throughout and if the rate of closure through the portion which gives fairly high valve resistance may be considered as uniform (say the last 15% of valve movement), the diagram of Fig. 10 may be made to apply fairly closely by dividing the time of making the effective portion of the closure by 0.15 (or whatever the proportional closure is for the effective portion of closure) and using the quotient as the full time of closure. It will be seen that considerable pressure is developed even with long-time closure. For gate valves a similar method of computation may be used.

If the resistance of the valve through the last part of closure were maintained in such a way that P would remain constant, the time required to make this part of the closure would be

$$t = \frac{0.0135\ lv}{P} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (16)$$

It is not practicable to obtain such a valve movement. For ordinary methods of closing, the pressure will necessarily be variable and the maximum pressure will, in general, be larger than that given by this equation. The dotted curve of Fig. 10 gives the pressures calculated by equation (16). In this diagram, the abscissas represent the full time of closing the valve. If the effective portion of closure be considered, i. e., the portion which gives relatively high resistances, the corresponding full time of closure at uniform rate should be used as the abscissa; thus, if the effective portion of closure is the last one-sixth of the valve movement, and this is made at a uniform rate in five seconds, the pressure found by equation (16) may be taken from the dotted line of the diagram by using 30 seconds as the time. Even with this interpretation, the formula is not accurate. Equation (16) has often been applied to cases of sudden closure of valve, an incorrect application unless modified by the springiness of the water and pipe.

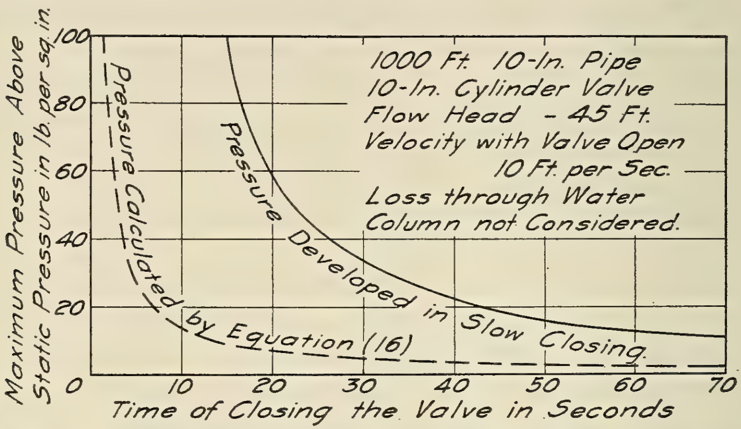


FIG. 10. CALCULATED MAXIMUM PRESSURE FOR SLOW CLOSURE OF CYLINDRICAL VALVE AT A UNIFORM RATE.

18. *Size of Relief Valve.*—It is the purpose of this article to indicate a rational method of obtaining the size of opening required for the relief valve.

Let the velocity in the supply line be represented by v. Consider that the relief valve keeps the pressure down to some value P lb. per sq. in. above static pressure, and that p is static pressure. The pressure P may be considered to be generated according to the law of water hammer. To produce this pressure P, then, the velocity in the pipe must be reduced by an amount v'. The formula for pressure produced by water hammer may be written $P = hv'$, where h is the coefficient by which the change in velocity v' is multiplied to find the pressure produced; h may be called 54 for the pipes ordinarily used for supply lines. The velocity in the pipe is now $v - \frac{P}{h}$ feet per second. The water must now all flow through the relief valve. The pressure at this point is P lb. per sq. in. above static pressure or 2.3 P feet of head. If A is area of pipe, a the area of relief valve and c the coefficient of discharge of the relief valve, then

$$A\left(v - \frac{P}{h}\right) = ca\sqrt{2g\text{x}2.3(P+p)}$$

$$a = \frac{A\left(v - \frac{P}{h}\right)}{c\sqrt{4.6g\,(P+p)}} \qquad \text{(17)}$$

Substituting $h = 54$ and simplifying,

$$a = \frac{v - \frac{P}{54}}{12.2c\sqrt{P+p}}A \qquad \text{(18)}$$

The value of the coefficient of discharge c of the relief valve depends upon the shape and amount of opening and upon the conditions just inside the valve; the valve may open freely into air, or the passages may be constricted at places before reaching the outlet, conditions which will cause great differences in the coefficient of discharge. The coefficient of discharge may be determined by blocking the valve open and testing its discharging capacity separate from the water column itself. The range of the coefficient, based on the nominal size, is from 0.2 to 0.6. If the outlet is constricted it will be less.

To illustrate the use of the formula, assume a long supply line in which maximum water hammer is likely to occur. Assume a velocity of 10 feet per second, and that it is desired to limit the maximum pressure to 50 pounds per square inch above the static pressure of 30 pounds per square inch. Assume $c = 0.3$.

$$a = \frac{10 - \frac{50}{54}}{12.2\text{x}0.3\sqrt{50+30}}A$$

$$a = 0.44\,A$$

If the supply line was 12 inch pipe, the effective area of relief valve should be $0.44 \times \frac{\pi}{4} \times 144 = 49.6$ square inches when the valve is fully open.

This method has had experimental verification.

In connection with the subject of relief valves, attention may well be called to the internal relief valve in water columns V and XIV. The relief valve forms the seat for the cylindrical valve of the water column. The location of the relief valve is a favorable one, and the size is adequate.

19. *Summary.*—The following comments on the work are offered.

1. The tests give the loss of head for various rates of discharge in the principal types of locomotive water columns in use in the United States. The loss through the valve and through the riser of the water columns were each determined.

2. At a discharge of 4000 gal. per min. the loss of head through the water columns ranged from 15.4 ft. of head to 46.5 ft. of head. The resistance to flow is surprisingly high,—much higher than has usually been estimated. It is evident that the discharge of water columns under working conditions is smaller in many cases than has been estimated. It is worth noting that the water columns which give high resistances include types which are used in large numbers by the railroads of the country.

3. A comparison with the frictional losses through pipes and elbows will help to give a fuller conception of this high loss of head. For the water column which gave the highest resistance, the loss of head is equal to the frictional loss for the same discharge through a 10-in. line of straight pipe 566 ft. long. Similarly this loss is 25 times as much as that through a 10-in. elbow. To get an adequate discharge through such a water column will require a greater elevation of tank and involve a larger expense in pumping than is necessary.

4. An examination of some of the types shows that the forms of the valves and passages do not accord with the principles of good hydraulic design. Sudden change in direction, sudden contraction and expansion of the section of the stream, and tortuous passages are among the objections to be found, and high local velocities are especially troublesome. Mechanical features of

construction, inspection, and repair seem to have crowded out consideration of hydraulic efficiency. Modifications in the design of some of the water columns, made since the first tests were conducted, have resulted in improved hydraulic conditions without loss in mechanical efficiency.

5. The telescopic adjustable spout with its large cross-section shows lower losses than the fixed spout, though it must be borne in mind that the point of discharge taken in water columns with telescopic adjustable spouts is at the end of the riser, and that for this reason the lift is greater than with the fixed spout. The ball-and-socket spout gives about the same friction loss as the rigid spout, but it has the advantage that the point of discharge is usually lower. It may also be noted that the anti-splash devices use up head in providing a solid stream.

6. The maximum velocity allowable through a water column will depend upon such matters as the satisfactory operation of the valve and also upon the effect of closing the valve in the development of water hammer in the supply main. With a short line from the supply tank, a velocity of 12 or 15 ft. per sec. through the water column may be considered as the maximum desirable velocity for ordinary conditions, and for longer lines the limiting velocity may perhaps be as low as 8 ft. per sec. It would seem that 3000 gal. per min. for an 8-in. water column, 4000 gal. per min. for a 10-in. water column, and 6000 gal. per min. for a 12-in. water column may be considered to be the limit of desirable discharge. Considerations of the cost of pipe line and supply tank required to give the above discharge in a proposed installation may show that such high velocity and discharge are uneconomical, and on the other hand it is possible that high available heads or long and expensive supply lines may make higher velocities permissible. It will be seen that the velocities named are much above the limiting velocities of ordinary waterworks practice. It would seem also that for the rates of discharge just noted the allowable loss through the water column itself should not be much more than 20 ft., and that the limit may well be placed at less than 20 ft.

7. The method outlined for making calculations of the losses of head and discharge in water service installations is a convenient one. By means of the diagrams for friction in pipe and elbows and the diagrams for loss through the water column and

the use of the trial ratio, the discharge given by any flow head may be calculated without the labor attendant upon the use of the usual formulas for flow of water in pipes.

8. The examples of combinations of pipe lines and water columns given in Table 6 illustrate the distribution of losses in such installations. There is an advantage in a large pipe by reason of the large discharge for a given head and also in the smaller opportunity for water hammer. In an installation having a high head available (as in some gravity lines) the pipe may well be smaller than in the common installation, provided the arrangement of the valve closure guards against water hammer and proper relief valves are used.

9. The water hammer pressure generated in a pipe line when a valve is closed suddenly and no relief valve is used, for the sizes and thicknesses of pipe used in ordinary water service installations, will be, in lb. per sq. in., about 54 times the velocity of water in the pipe in ft. per sec. The term "sudden closure" is here taken to mean that the time consumed in that part of the valve movement which gives relatively high valve resistance is less than the time required for the pressure impulse to travel from the valve through the pipe line to tank and back at a speed of about 4000 ft. per sec. This effective portion for all but two of the water columns tested was the last 15% of the valve movement. For slower closures the pressures developed will be smaller than the maximum water hammer, the amount depending upon the resistance offered by the valve opening, the head of the line, etc.

10. For a slow closure the resistance through the valve opening is the chief force in stopping the mass of water.

11. In all but one of the water columns tested the resistance through the valve opening was not markedly larger than that at full opening until the valve had attained at least 85% of its closure. Since during the first 85% of the valve movement, little work is done in stopping the water, and since during this portion of the valve movement water hammer will not be developed even with rapid closing, it follows that it is immaterial how quickly this first 85% of closure is made. The time thus saved may well be used in lengthening the time for the remaining 15% of closure. The time-pressure diagram and the valve-movement-pressure diagram of one of the newer forms of water column illustrate the

hydraulic advantages which may be gained in this way. The effect in this case is the same as if a uniform closure five times as long as the actual time of closure were used. It is seen that making the last portion of the valve movement slowly is very advantageous.

12. With the time-pressure and valve-movement-pressure diagrams, and knowing the head, diameter, and length of the pipe line, the pressure which will be developed when the value is closed in a given time (slow closure) may be worked out approximately by the method given under the heading "17. Pressure Produced by Slow Closure of Valve."

13. When a relief valve is used as an auxiliary device, the size of the effective opening through the relief valve itself may be calculated from equation (18). Although relief valves offer a protection against excessive pressure, they do not of themselves fully solve the problem of stopping the mass of water. The type of water column having an internal relief valve which forms the seat for the cylindrical valve itself may be expected to give relief from high pressure with rapid closing, provided it is proportioned to furnish the proper resistance to flow to suit the conditions of flow head and length of pipe line.

14. From general considerations it is reasonable to expect that 8-in. and 12-in. water columns will have losses approximately the same as those found in the 10-in. water columns at the same velocity of flow. Losses based on this assumption, then, may be used until more accurate information is available without chance of serious error.

APPENDIX

20. *Diagrams for Friction Loss in New Cast-Iron Pipe.*—Although not a part of this investigation, the diagrams for friction loss in new cast-iron pipe prepared for the Committee on Water Service are reproduced here as a convenience to readers of the bulletin. Calculations for friction loss in pipes are at best somewhat uncertain, since the properties of flow are more or less indefinite. The roughness of the pipe, the workmanship in laying, and other variations in hydraulic conditions act to give rather wide variation of flow under the same head. This is shown in the results of carefully made experiments which are accepted as standard work. Moreover, the difficulty of making experiments on pipe of medium and large diameters at high velocities has prevented the accumulation of as complete a set of data as could be wished. The best that can be done is to use the formulas and tables which most closely conform to well established data. Fortunately, it is generally not necessary to know the friction loss within close limits.

In Fig. 11 and 12, the loss of head in feet per 100 ft. of new straight cast-iron pipe for the discharge indicated by the abscissas has been plotted to logarithmic scale. Fig. 11 is for pipe having internal diameters from 3 in. to 10 in. and Fig. 12 for pipe having internal diameters from 8 in. to 24. in., though the extreme sizes in each diagram have little range of discharge. With a little practice, interpolation between lines may be made fairly accurately.

The diagrams (Fig. 11 and 12) are based upon the formula for pipe friction, $h=\frac{fl}{d}\,\frac{v^2}{2g}$, where h is the head lost in friction in l ft. of pipe, d is the diameter in feet, and v is the velocity in feet per second; f is a factor depending upon the size and roughness of the pipe, and varying with the velocity of the water; g is the acceleration of gravity in feet per second per second. The values of the coefficient f used in preparing the diagrams are those given in Merriman's Treatise on Hydraulics. For the sizes above 6 in. the results are substantially the same as may be obtained from the formula: loss in 100 ft. $= 0.044\,\frac{v^{1.8}}{d^{1.25}}$. The results for pipe of sizes 8 to 24 in. agree very closely with those obtained from the tables of Williams and Hazen for a pipe after approximately three years of service and also with the results of the excellent diagram given in Turneaure and Russell's Public Water Supplies. They also agree with the formula of Unwin, a noted English authority. The values found by the tables and diagrams just referred to do not differ by more than about 5 per cent from the values given by the diagram of Fig. 12 for the sizes named. It may be noted that this difference is much less than the variation in the results of experiments made at different times and places, and that a far greater difference may be expected with slight changes in the condition of roughness of the pipe. For sizes smaller than 8-in , the agreement of the several formulas is not so close. It is believed that the diagrams conform as closely to the results of experiments as any tables which have been published.

The values for head lost given by the diagrams for sizes from 8 to 24 inches diameter are generally smaller than those given by the Ellis and Howland tables and by the Darcy formula. A further difference is that these tables and formulas assume the head lost to vary as the square of the velocity, or nearly as the square, while the diagrams use 1.8 power. It seems that for high velocities, Ellis and Howland, and also Darcy, give a lost head which is higher than experiments show. The excellent form of the Ellis and Howland tables, as presented in the catalogs of the Addyston Pipe & Foundry Company, R. J. Wood & Co., and others, and the convenience of Weston's tables, which are based on the Darcy formula, have made these two sets of tables favorites for general use. It must be borne in mind, however, that for sizes above 6 inches, the lost head given by them for the higher velocities, is more than the actual loss.

21. *Diagrams for Velocity Head and Loss in Elbows and Tees.*—In Fig. 13 are plotted values of the velocity head $\frac{v^2}{2g}$ corresponding to discharges in gallons per minute through pipes having internal diameters of 8, 10, 12, 14, 16, and 18 inches. Although the scale is small, the values may be obtained with sufficient accuracy for the uses given in this bulletin.

With an assumed coefficient of entrance head, m, this diagram may also be used for finding the loss at entrance by merely multiplying the velocity head for the given discharge by the assumed coefficient. For ordinary forms of entrance this coefficient may be expected to be about 0.5, but it is not uncommon to use 1.0 for the coefficient, expecting that the larger value will cover other losses.

Fig. 13 also gives the loss of head in elbows of six sizes for given discharges in gallons per minute. The upper diagram is for elbows having a radius of curvature of axis of elbow equal to 1.5 diameters and the lower diagram for elbows having a radius equal to 3 diameters. The values are those selected by the Committee on Water Service as representing the maximum results of tests. Few data on large sizes and high velocities are available, but the values given in the diagrams are probably conservative and may be used until supplanted by more trustworthy information.

Fig. 13 also gives the loss of head in tees of six sizes for given discharges per minute, as presented by the Committee on Water Service. Information on the hydraulic properties of tees is even more incomplete than that of elbows, but the diagrams probably give the best results now available.

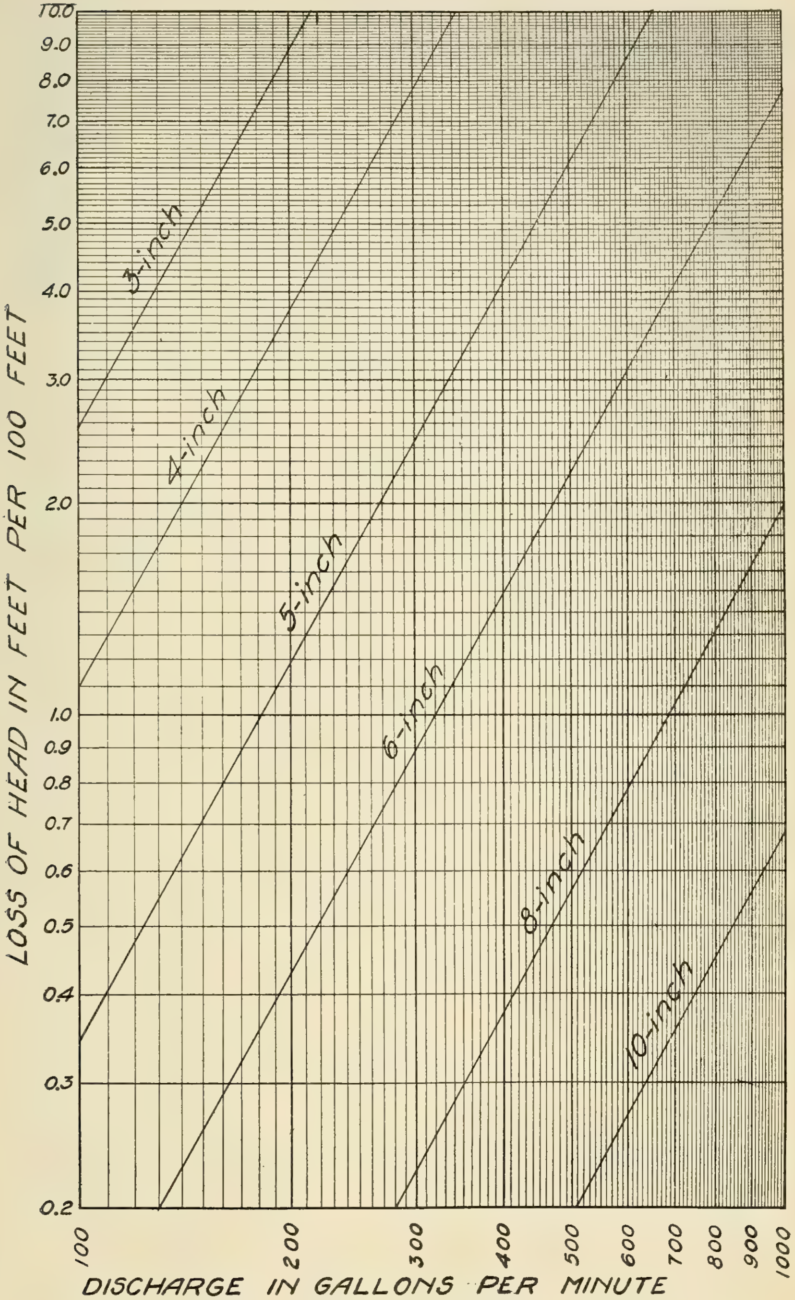


FIG. 11. LOSS OF HEAD IN NEW STRAIGHT CAST-IRON PIPE.

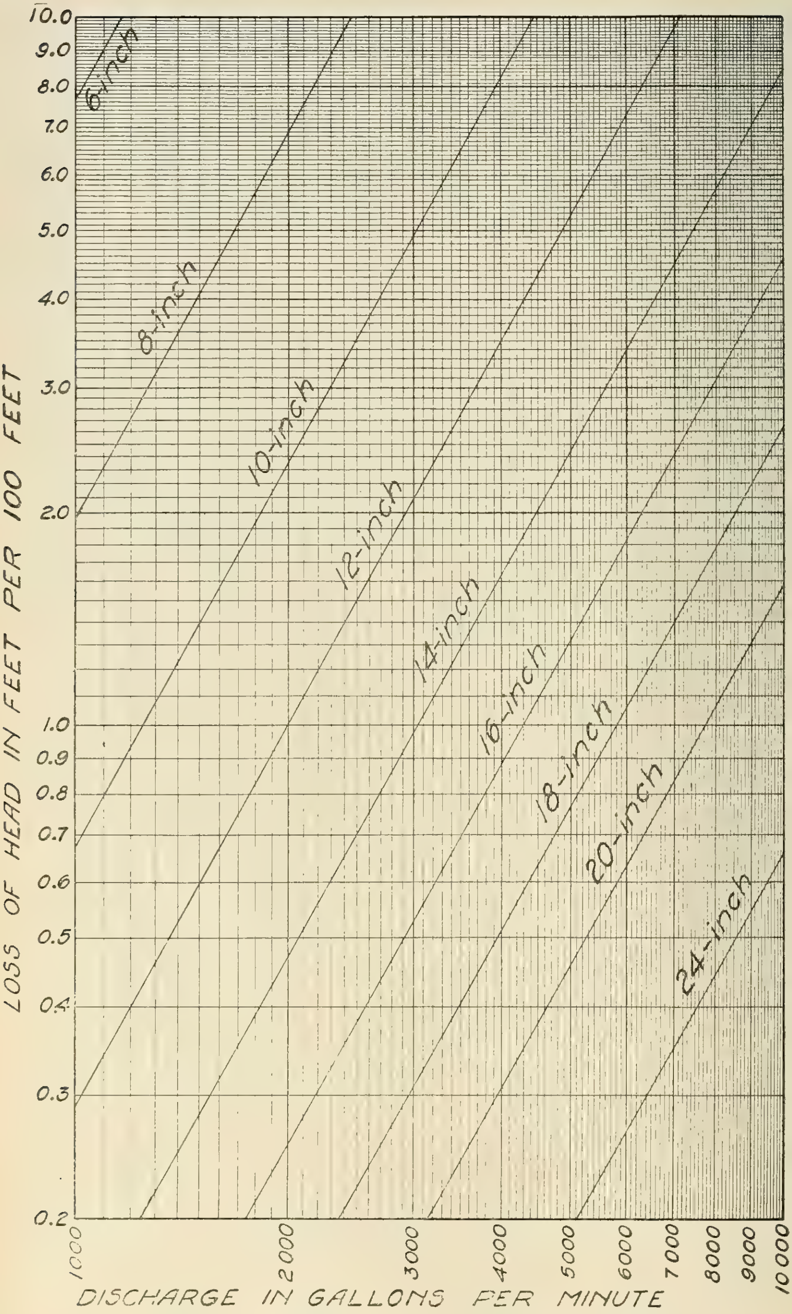


FIG. 12. LOSS OF HEAD IN NEW STRAIGHT CAST-IRON PIPE.

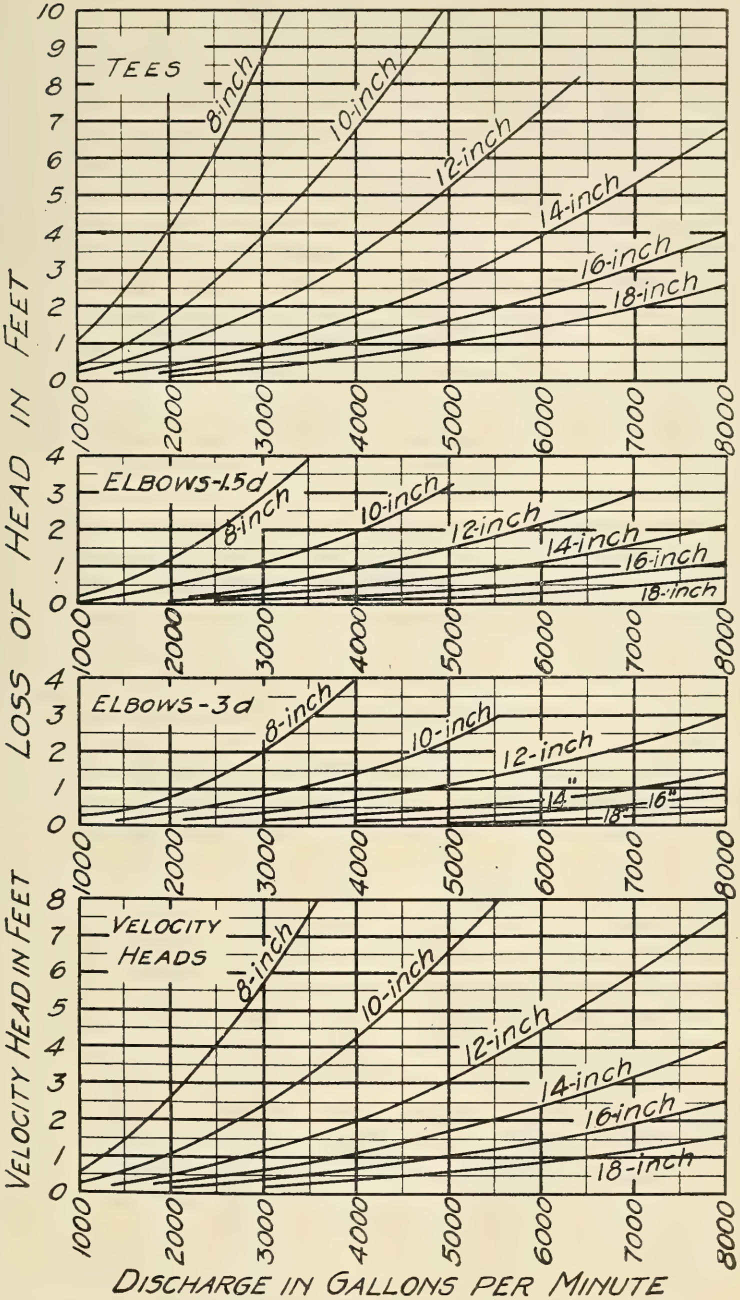


FIG. 13. DIAGRAMS FOR VELOCITY HEAD AND FOR LOSS OF HEAD IN ELBOWS AND TEES.

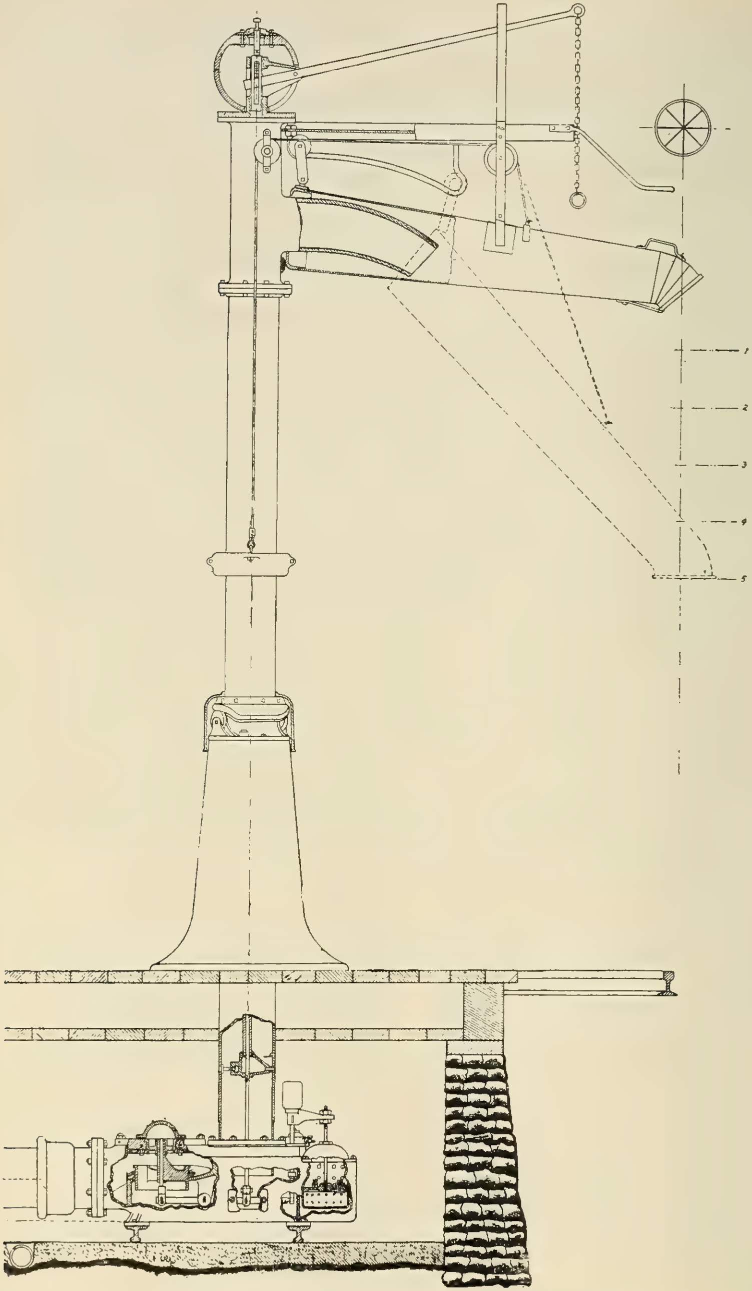


Fig. 14. Water Column I. (For details, see Fig. 42).

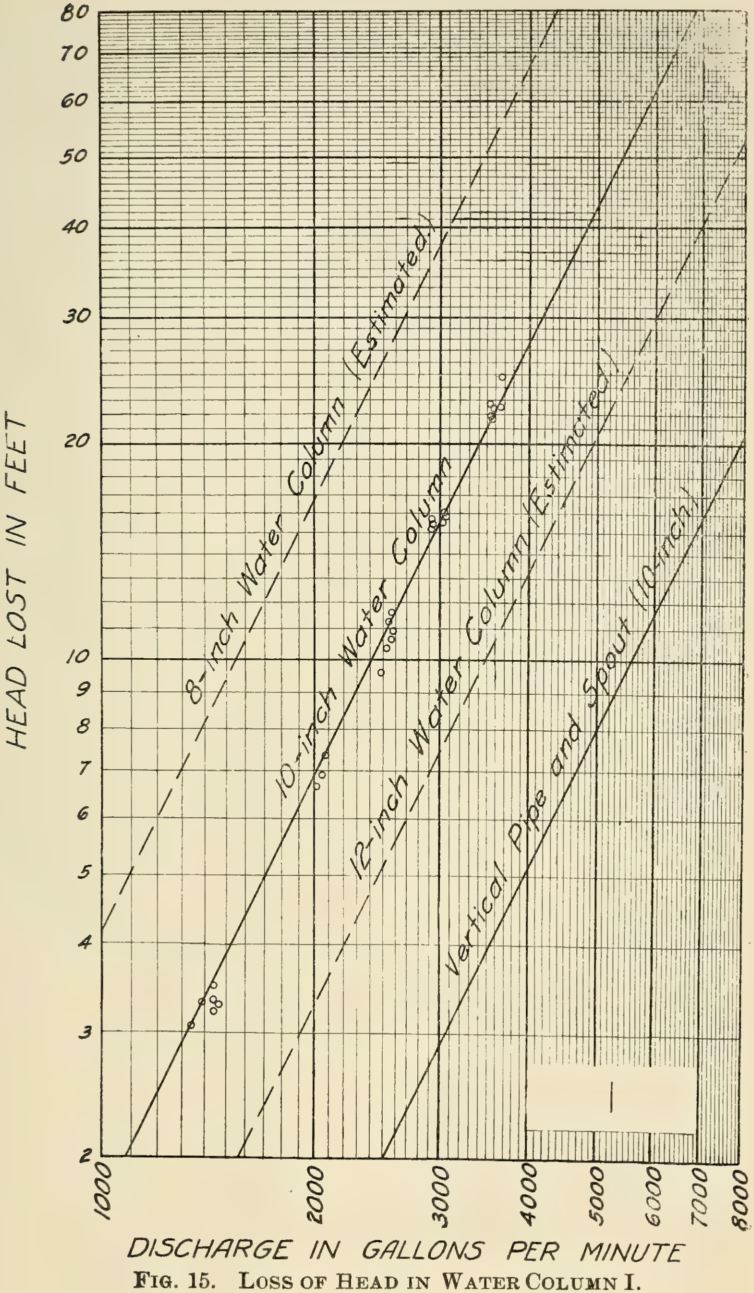


FIG. 15. LOSS OF HEAD IN WATER COLUMN I.

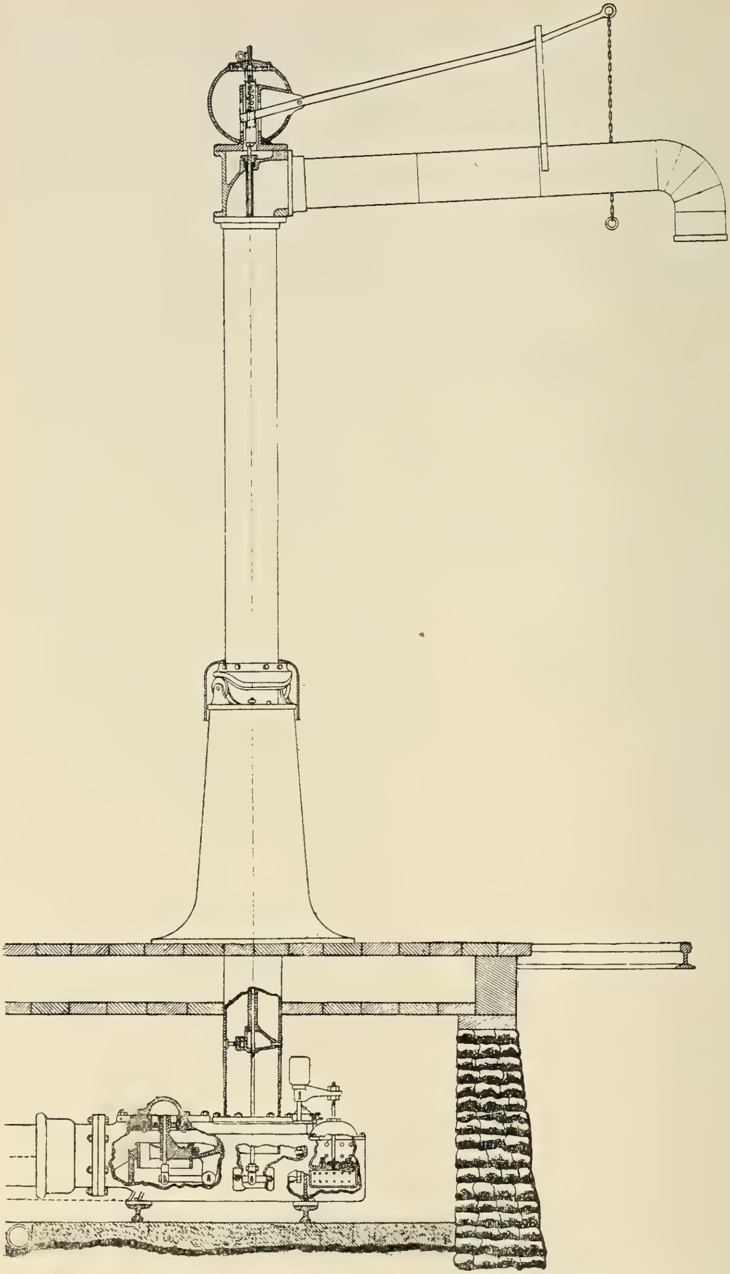


FIG. 16. WATER COLUMN II. (For details, see Fig. 42).

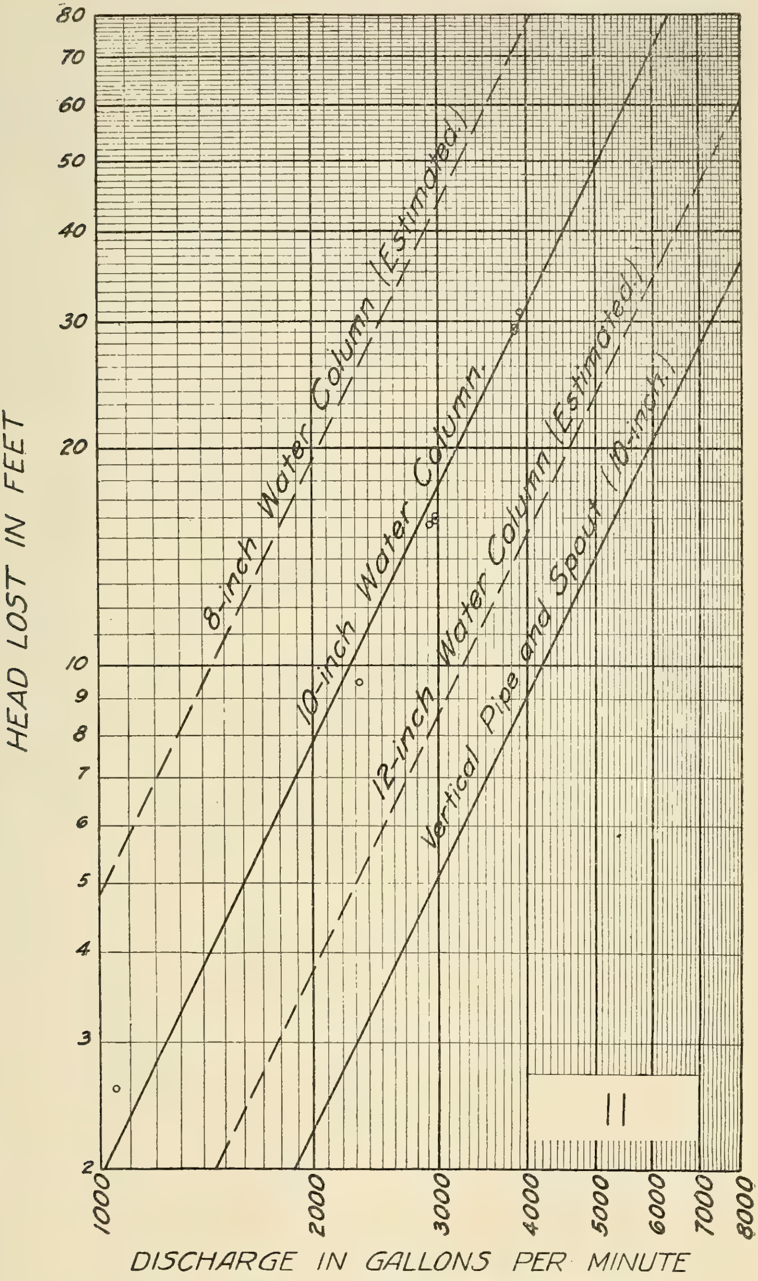


FIG. 17. LOSS OF HEAD IN WATER COLUMN II.

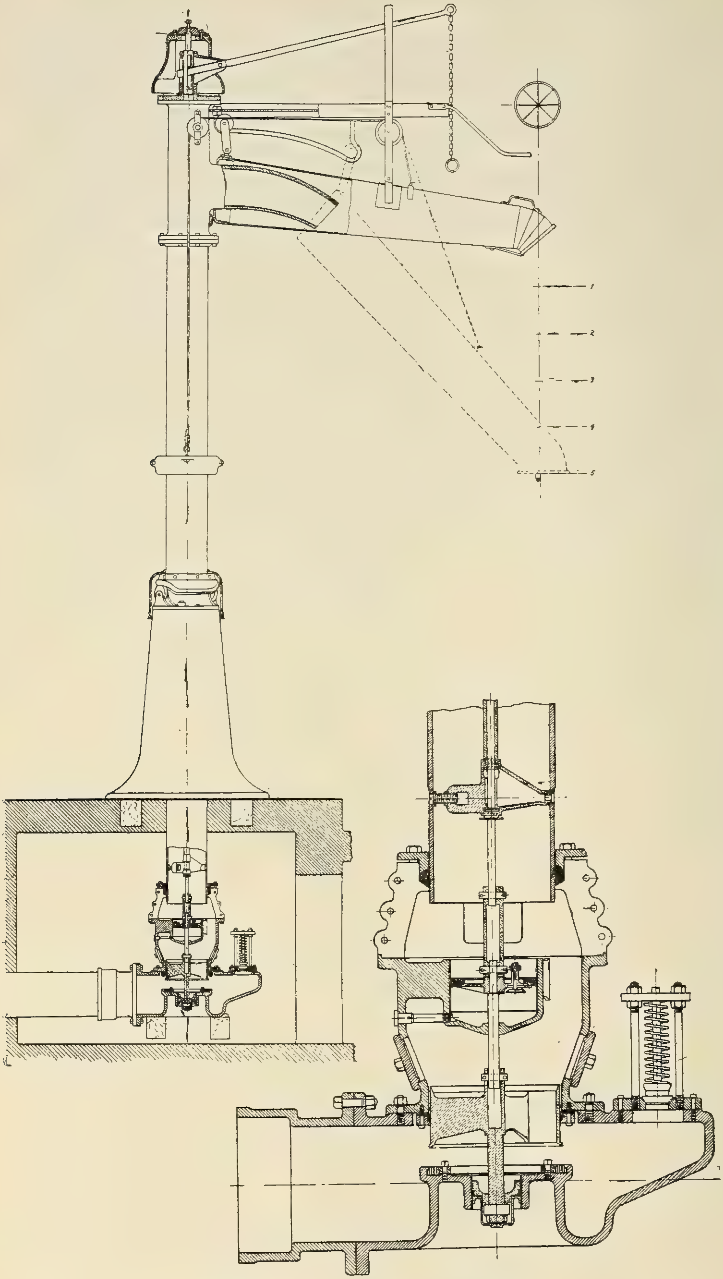


FIG. 18. WATER COLUMN III.

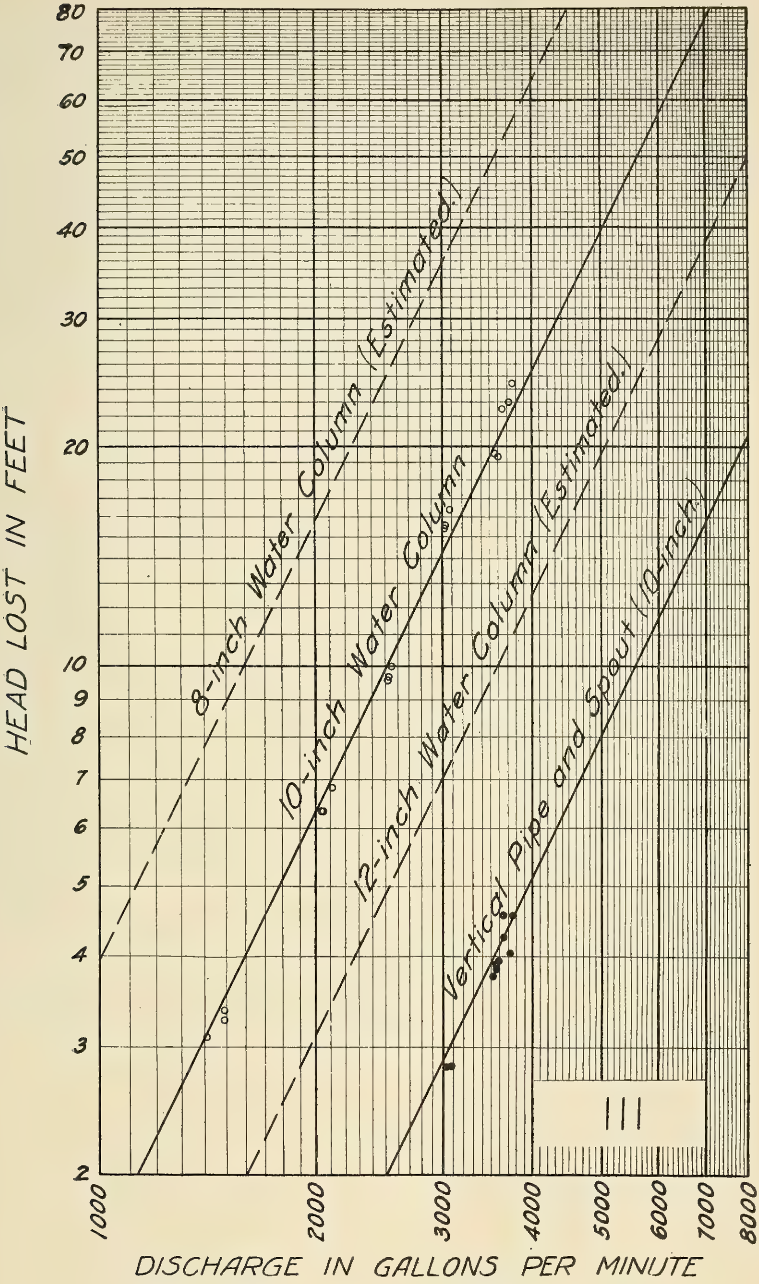


Fig. 19. Loss of Head in Water Column III.

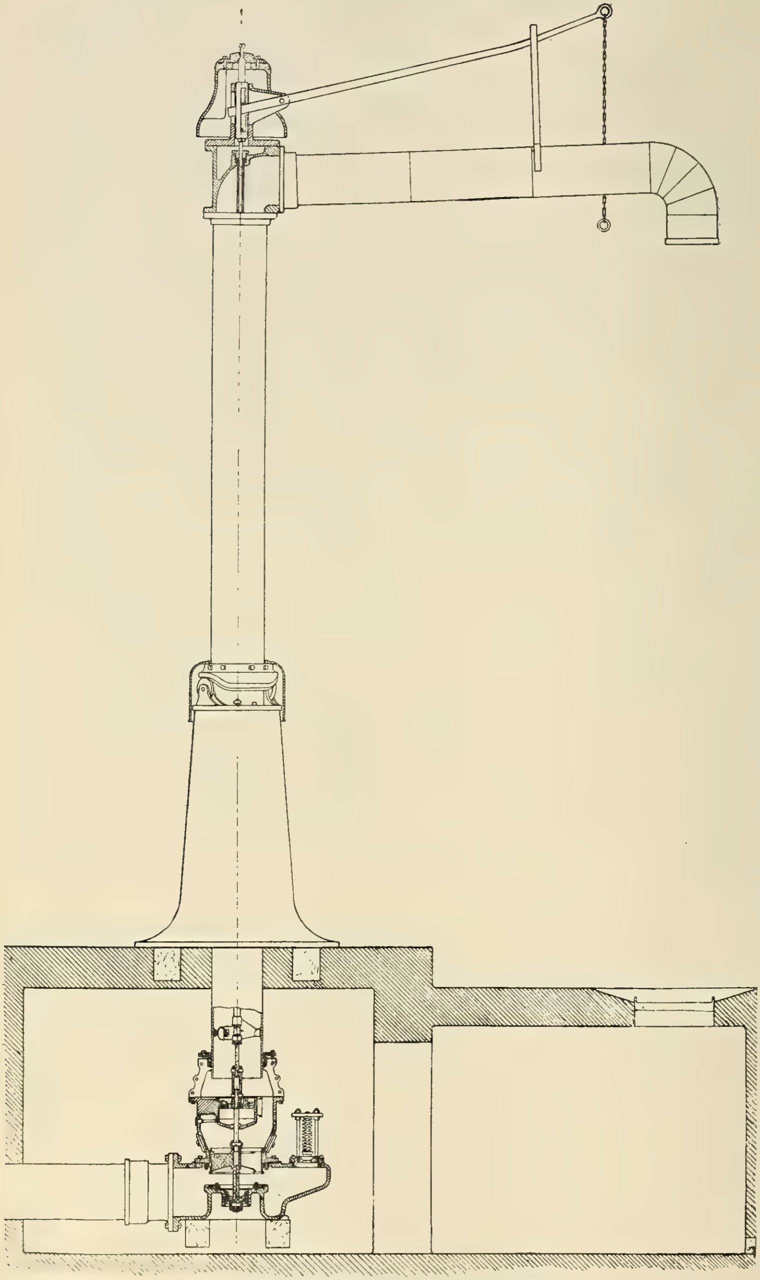


Fig. 20. Water Column IV.

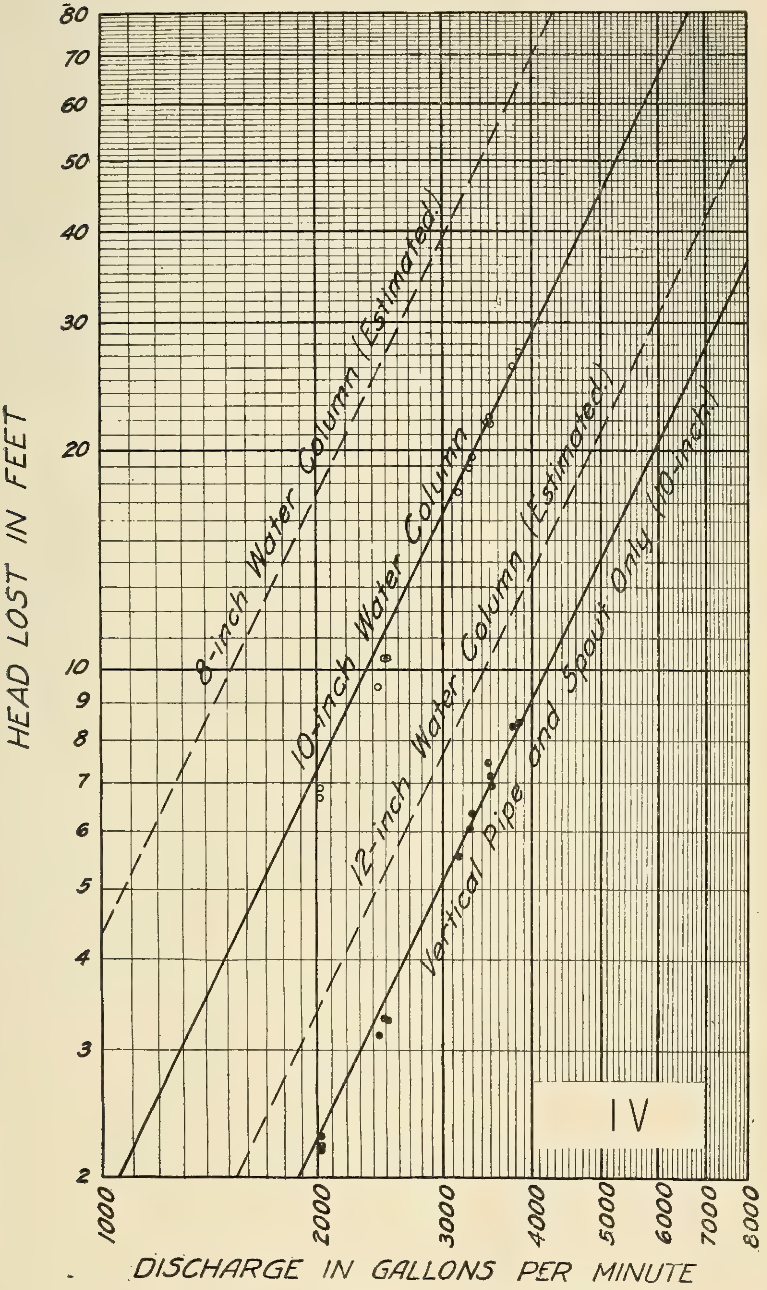


FIG. 21. LOSS OF HEAD IN WATER COLUMN IV.

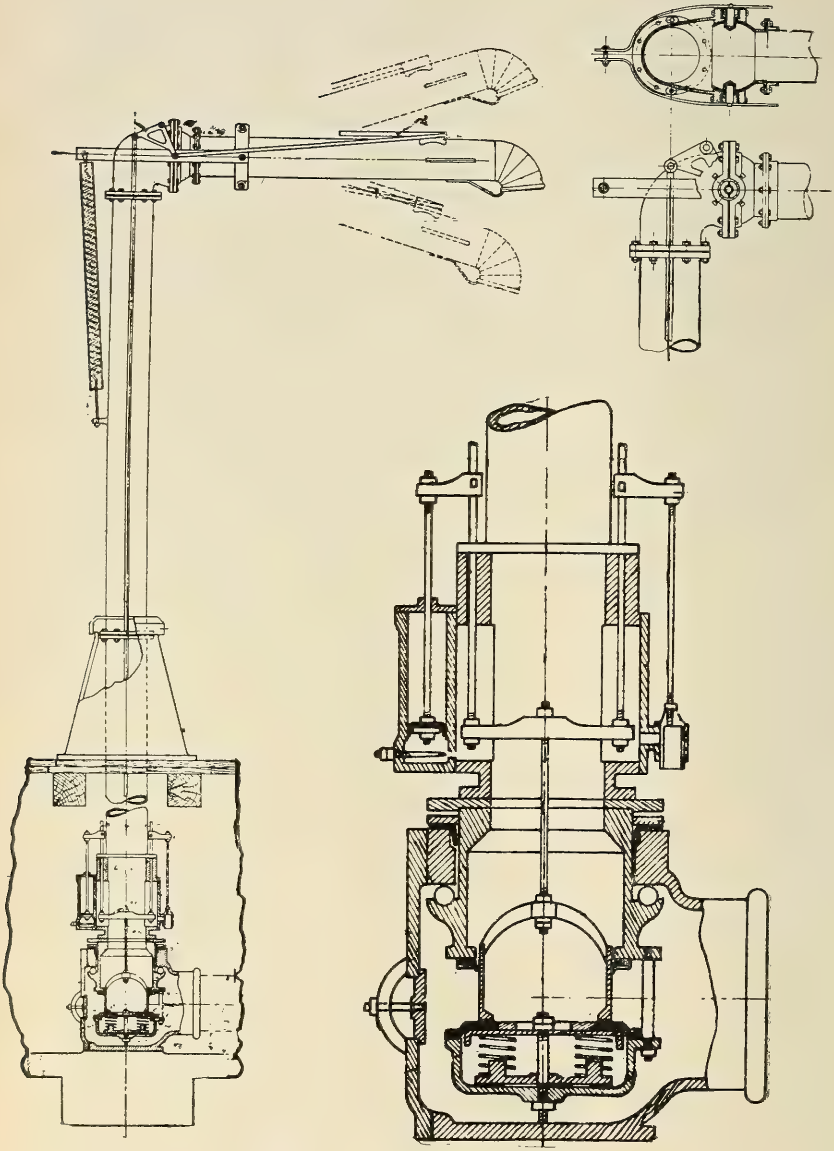


FIG. 22. WATER COLUMN V.

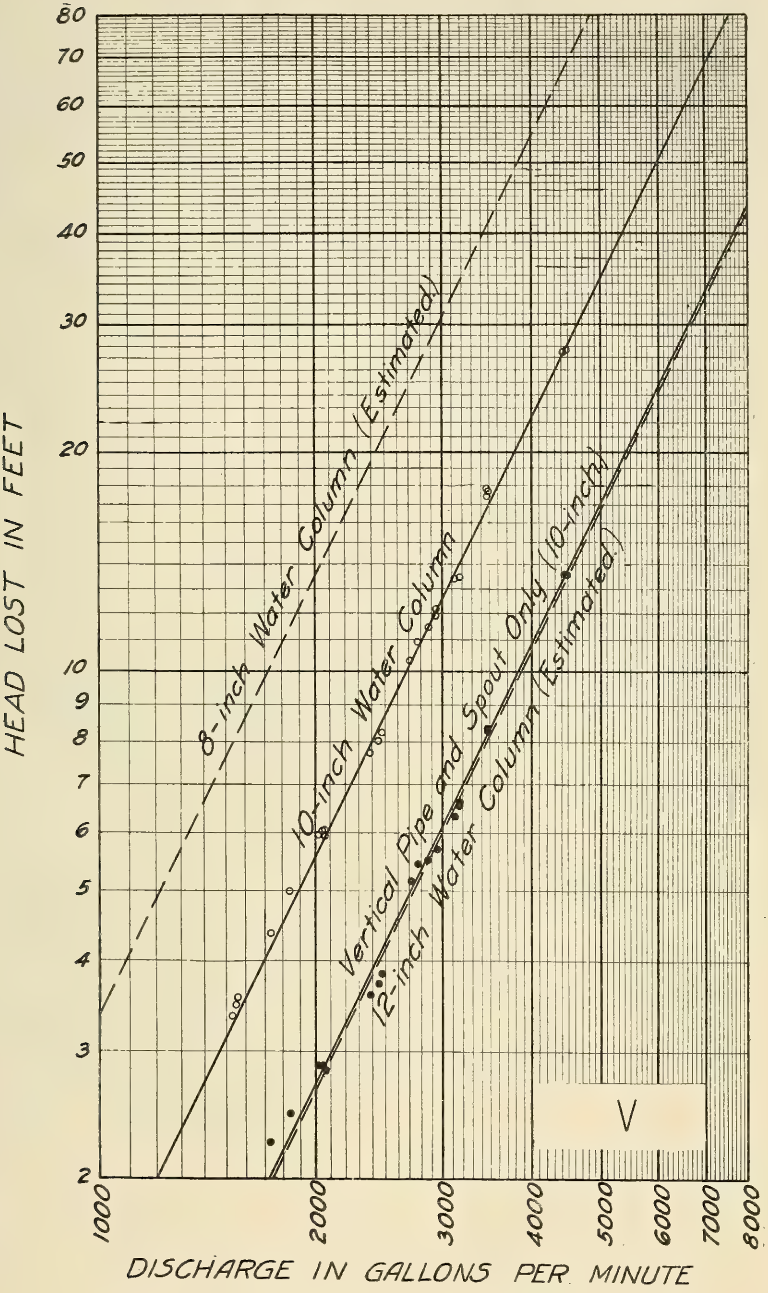


FIG. 23. LOSS OF HEAD IN WATER COLUMN V.

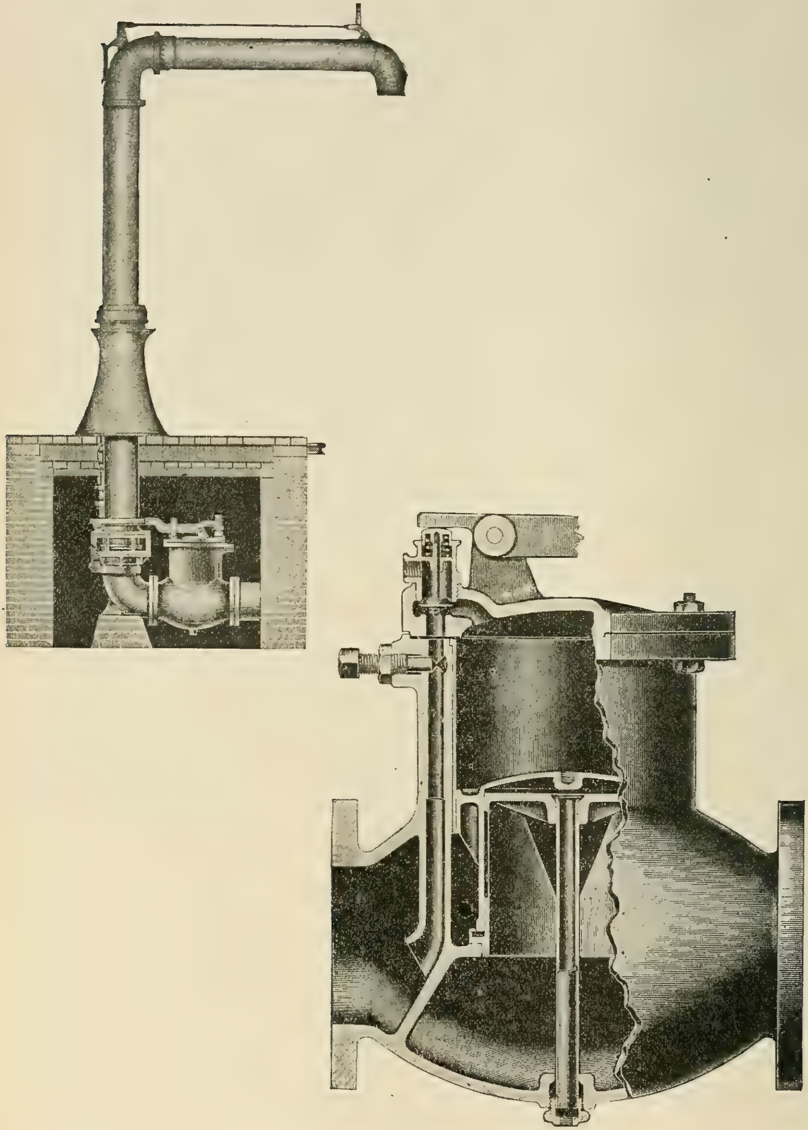


FIG. 24. WATER COLUMN VI.

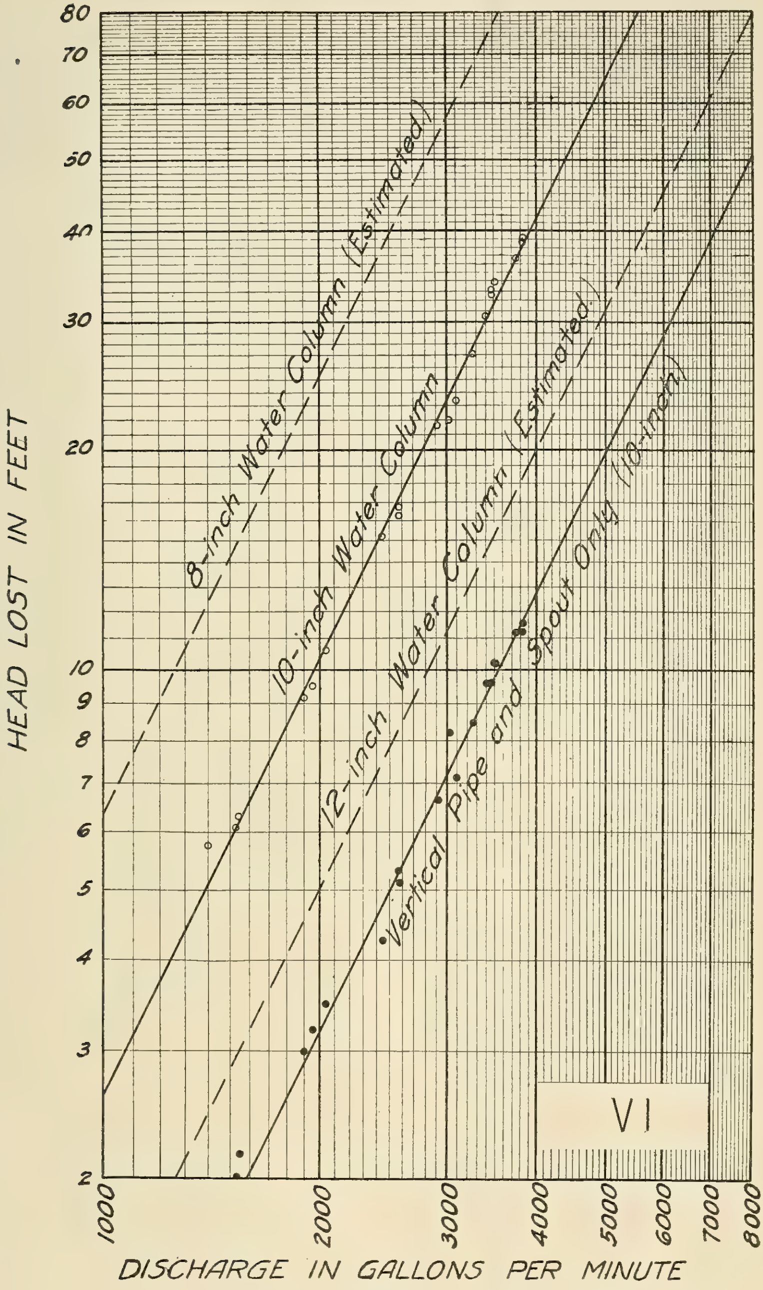


FIG. 25. LOSS OF HEAD IN WATER COLUMN VI.

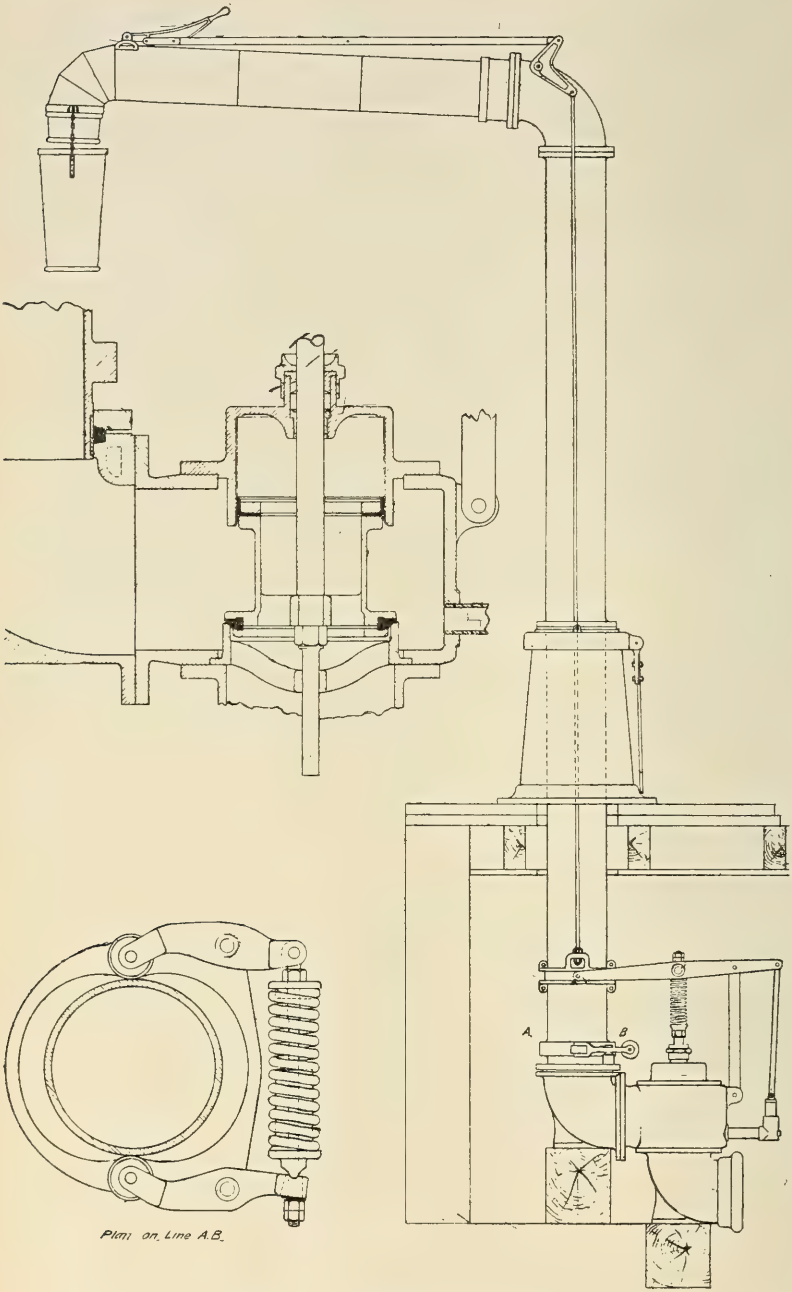


FIG. 26. WATER COLUMN VII.

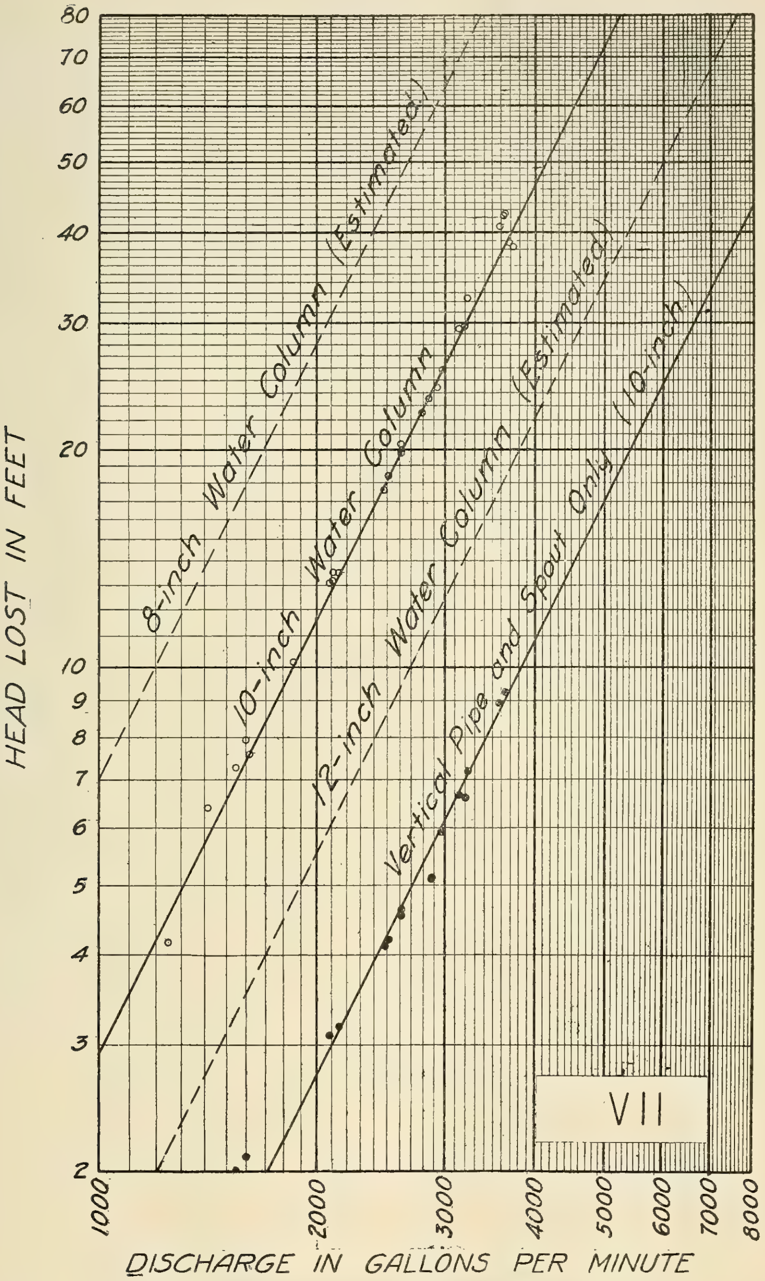


Fig. 27. Loss of Head in Water Column VII.

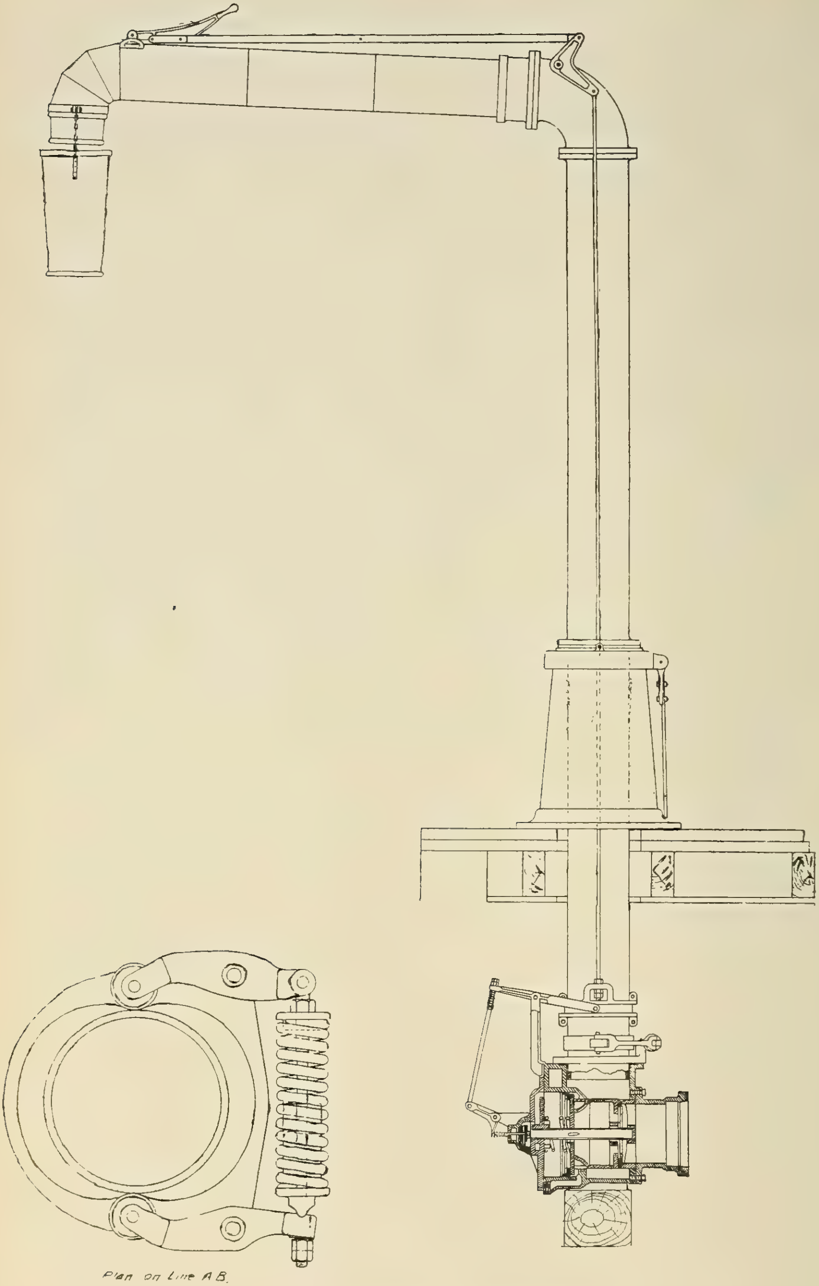


FIG. 28. WATER COLUMN VIII.

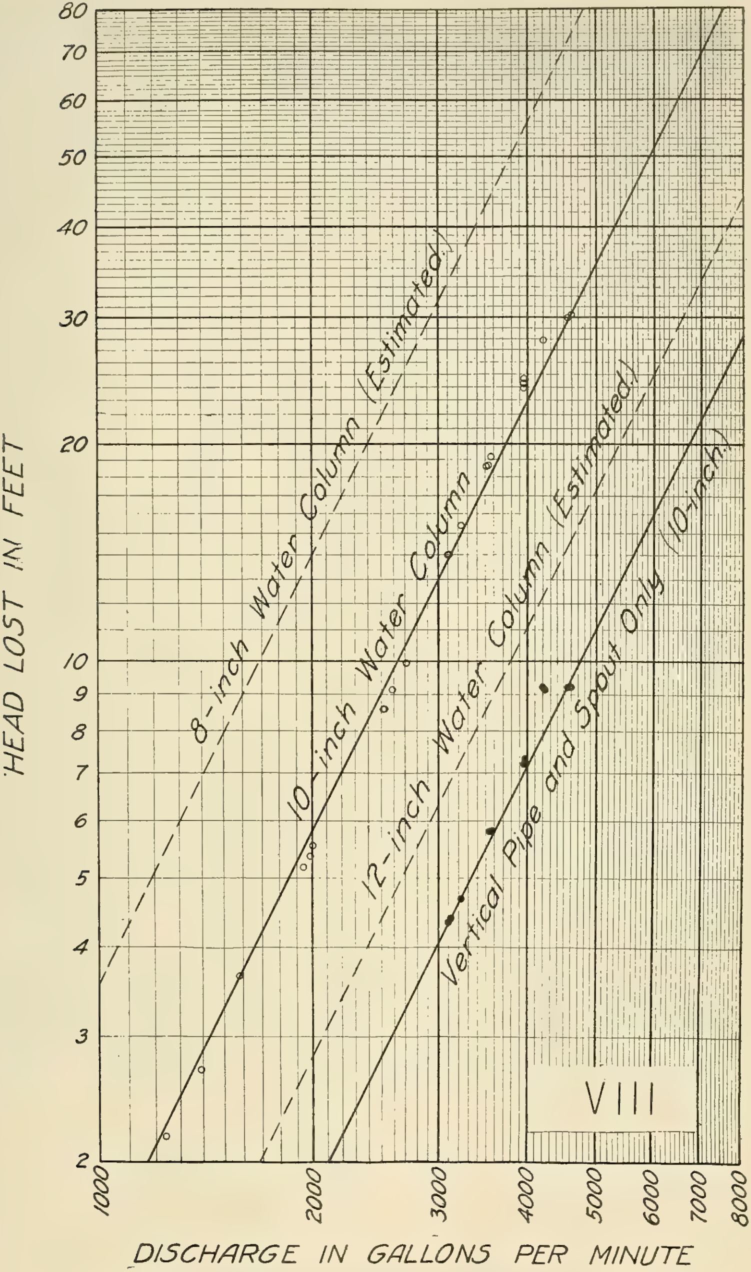


FIG. 29. LOSS OF HEAD IN WATER COLUMN VIII.

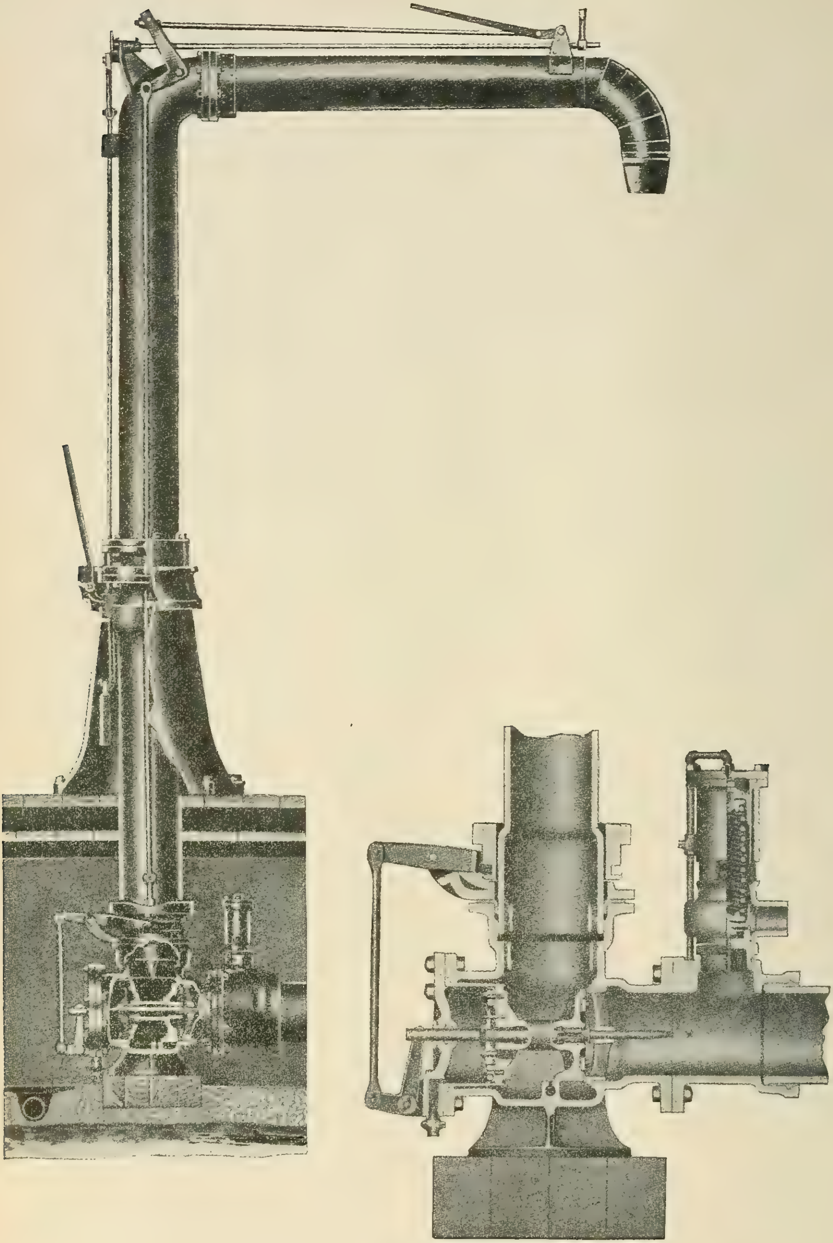


FIG. 30. WATER COLUMN IX.

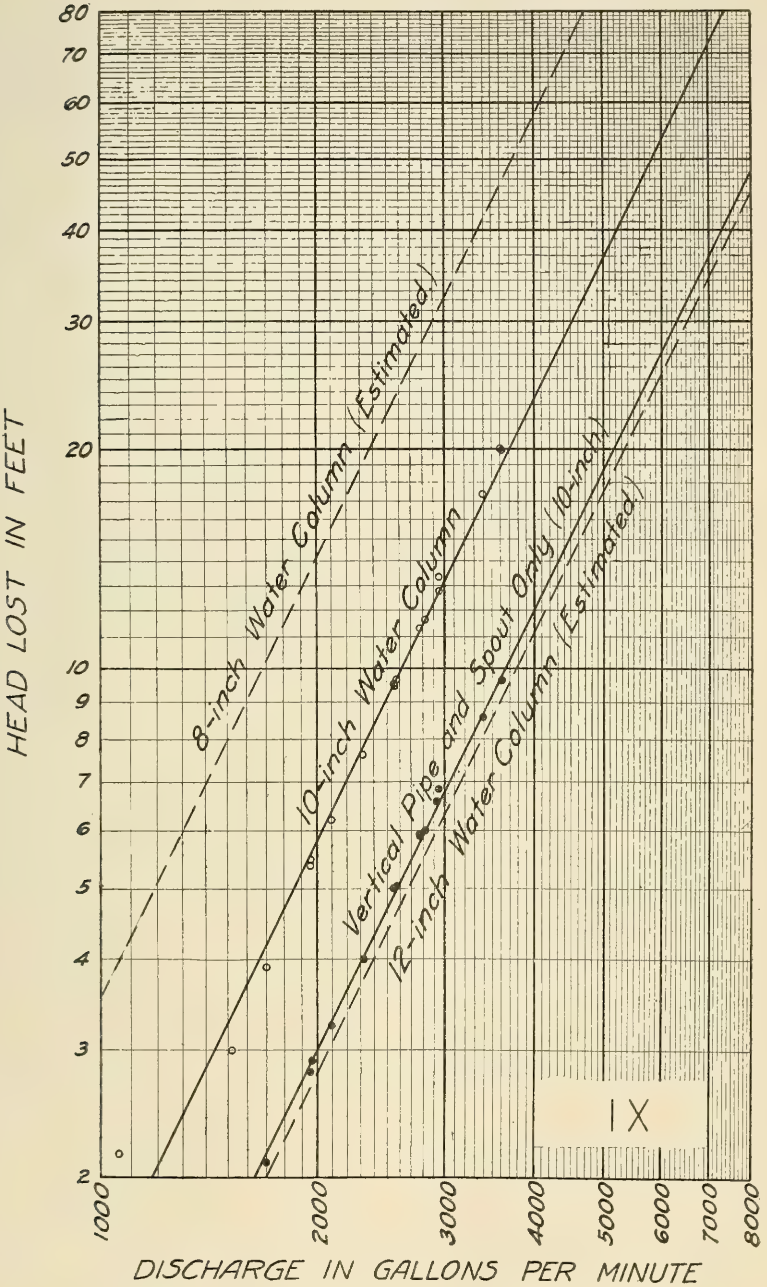


Fig. 31. Loss of Head in Water Column IX.

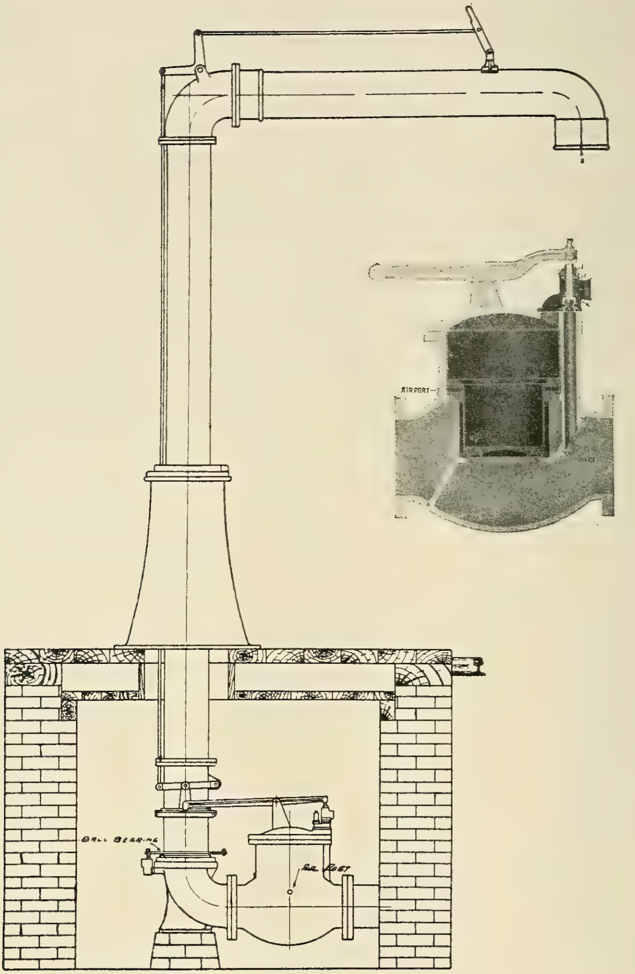


FIG. 32. WATER COLUMN X.

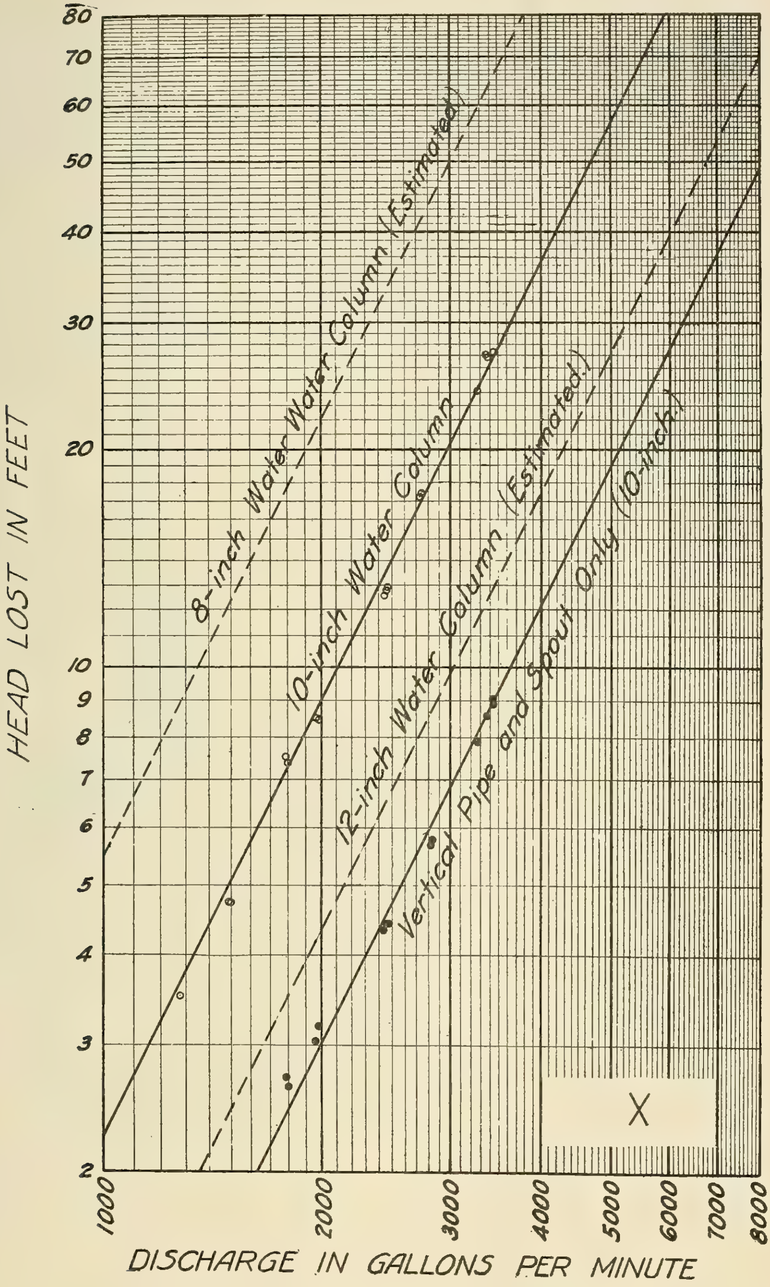


FIG. 33. LOSS OF HEAD IN WATER COLUMN X.

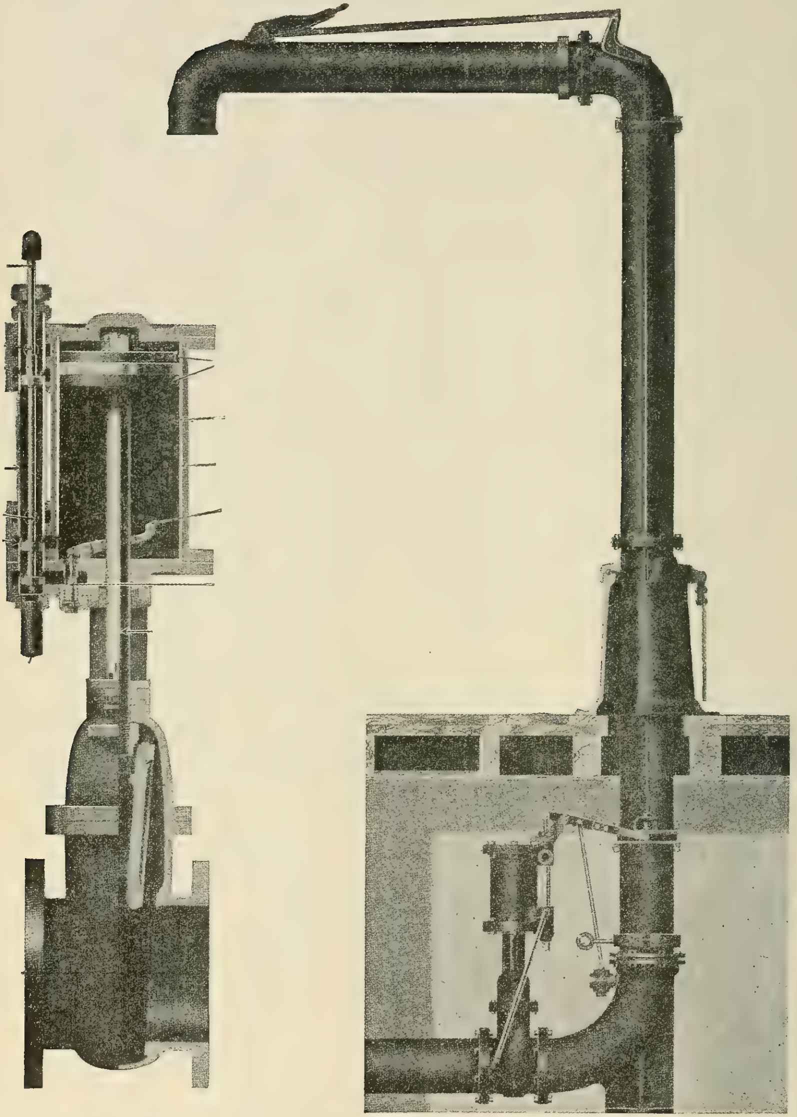


FIG. 34. WATER COLUMN XI. (In the test, the riser and spout of Water Column VI were used instead of those shown in the cut.)

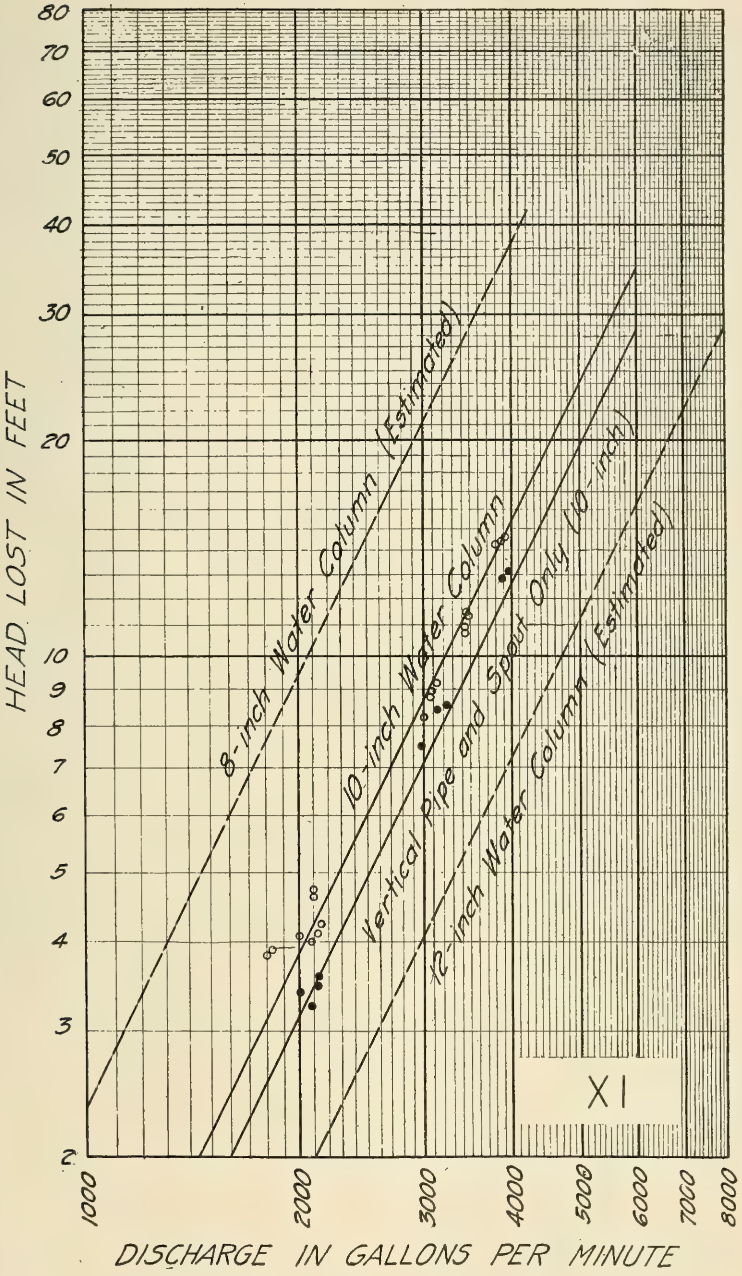


FIG. 35. LOSS OF HEAD IN WATER COLUMN XI.

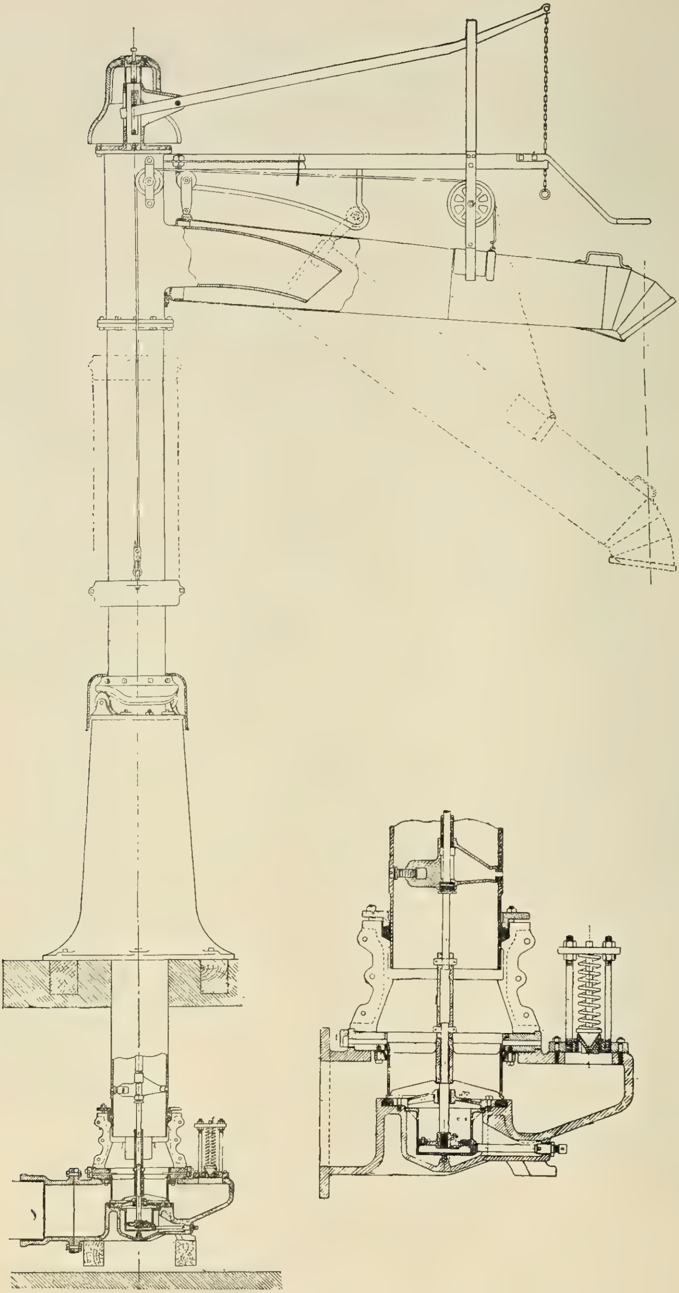


FIG. 36. WATER COLUMN XII.

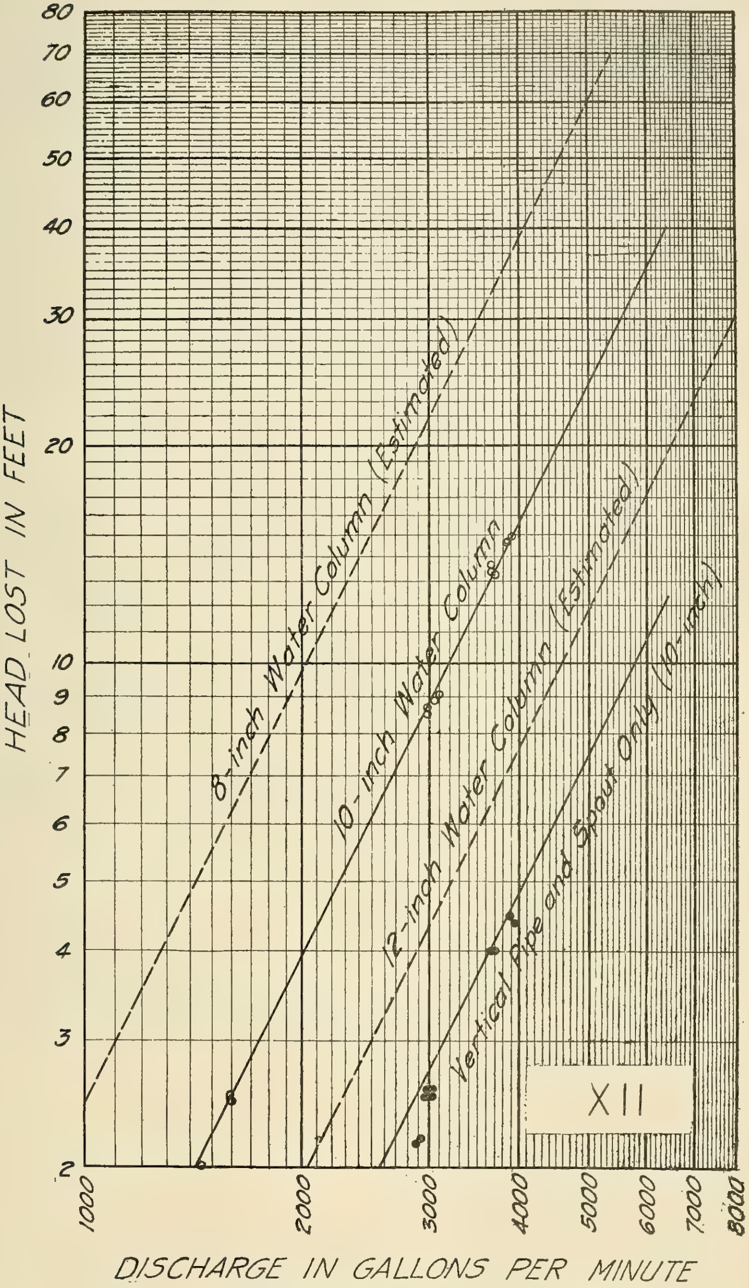


FIG. 37. LOSS OF HEAD IN WATER COLUMN XII.

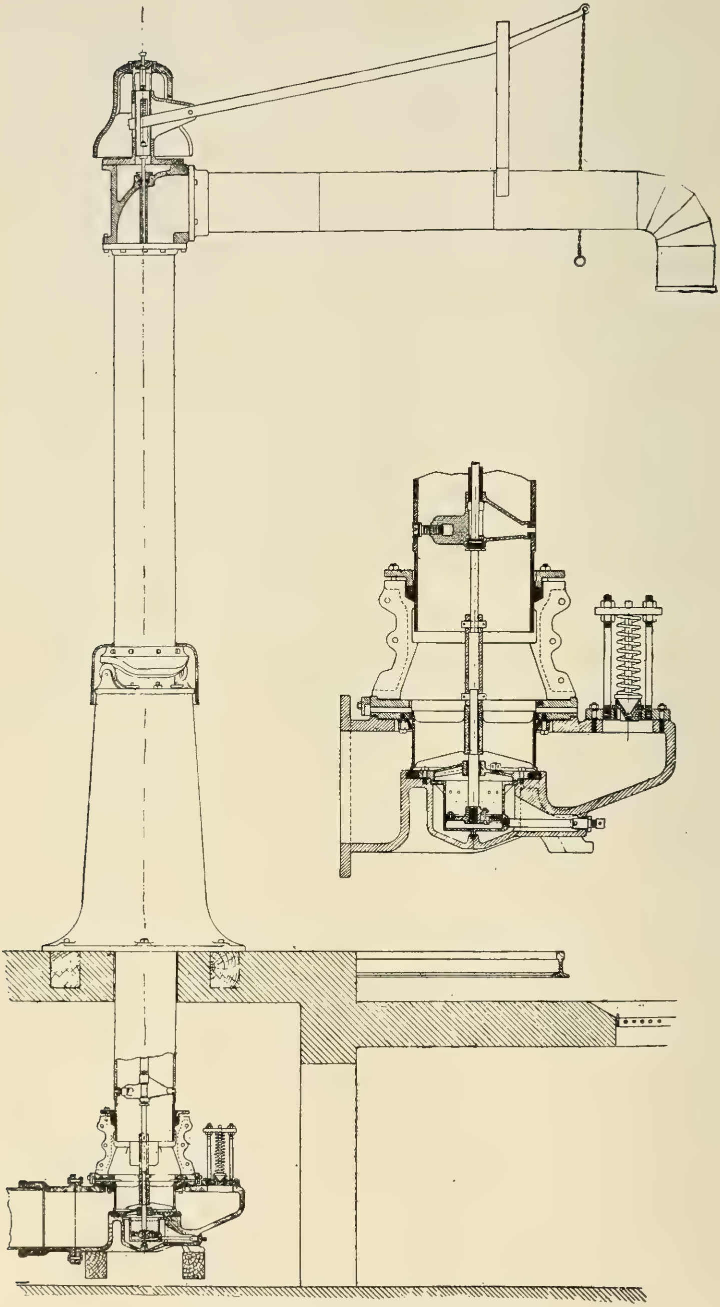


FIG. 38. WATER COLUMN XIII.

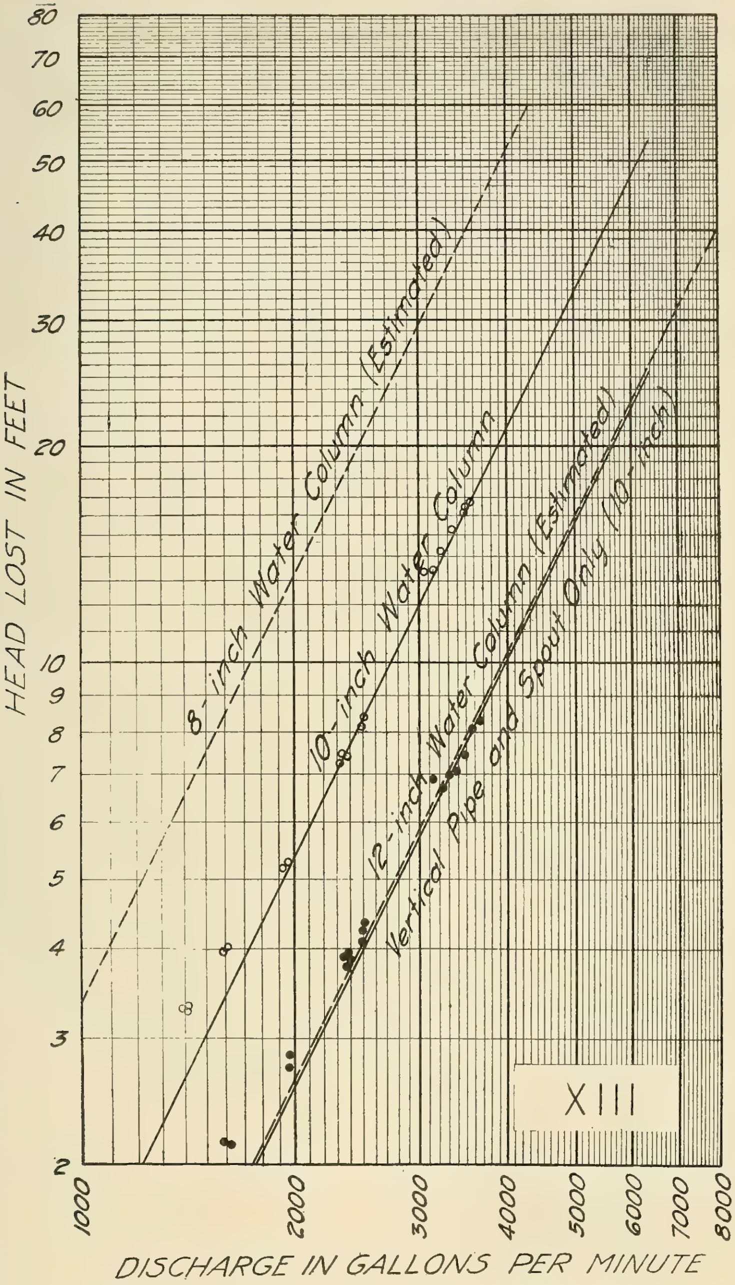


FIG. 39. LOSS OF HEAD IN WATER COLUMN XIII.

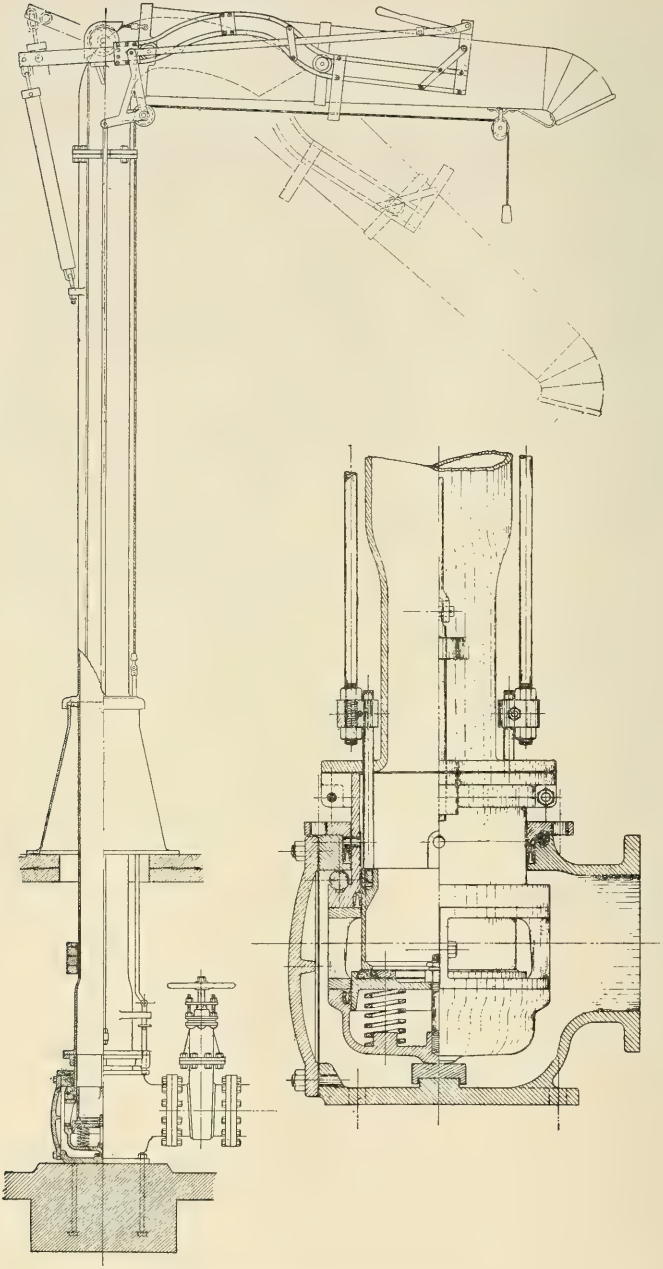


FIG. 40. WATER COLUMN XIV.

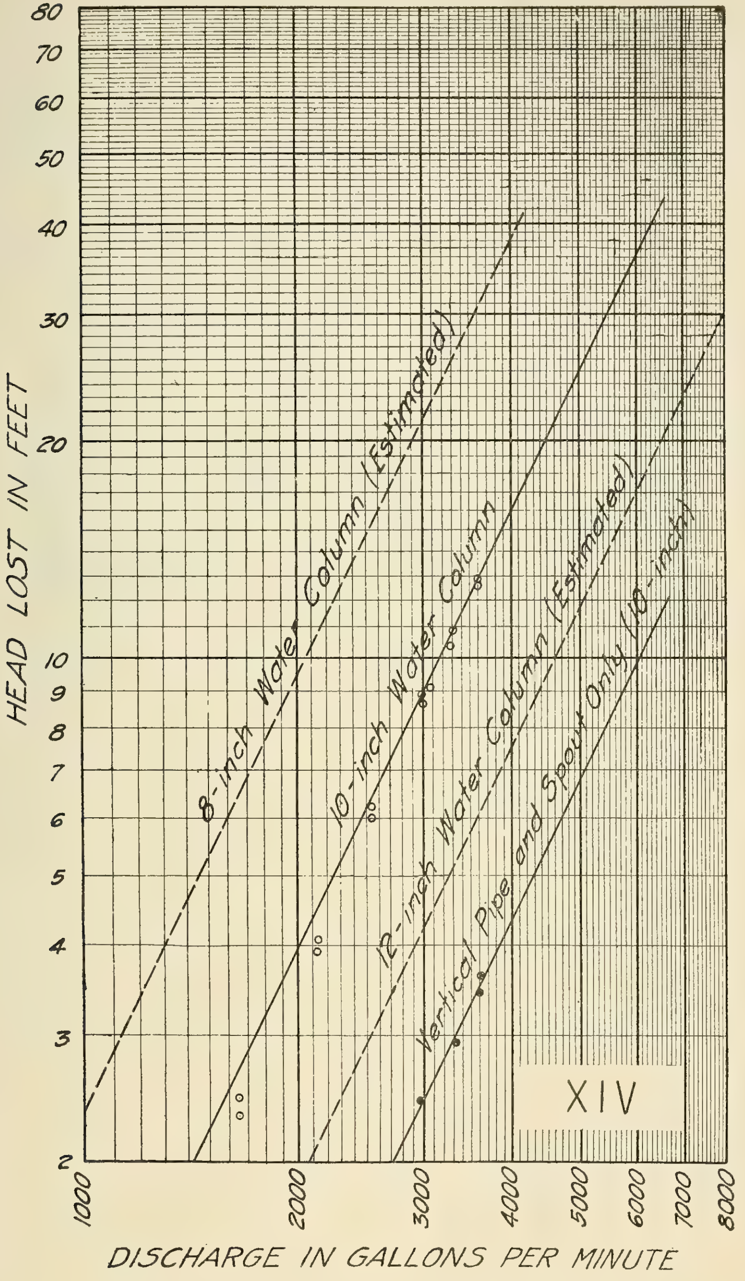
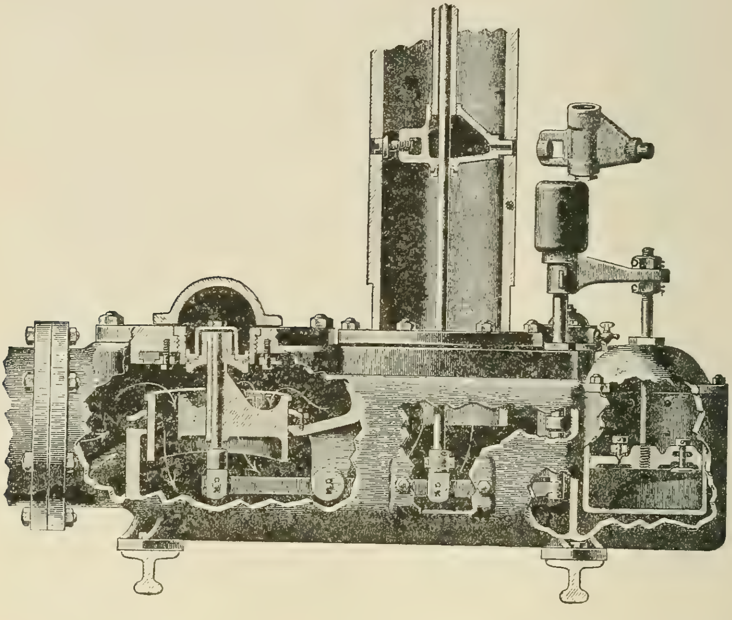


FIG. 41. LOSS OF HEAD IN WATER COLUMN XIV.



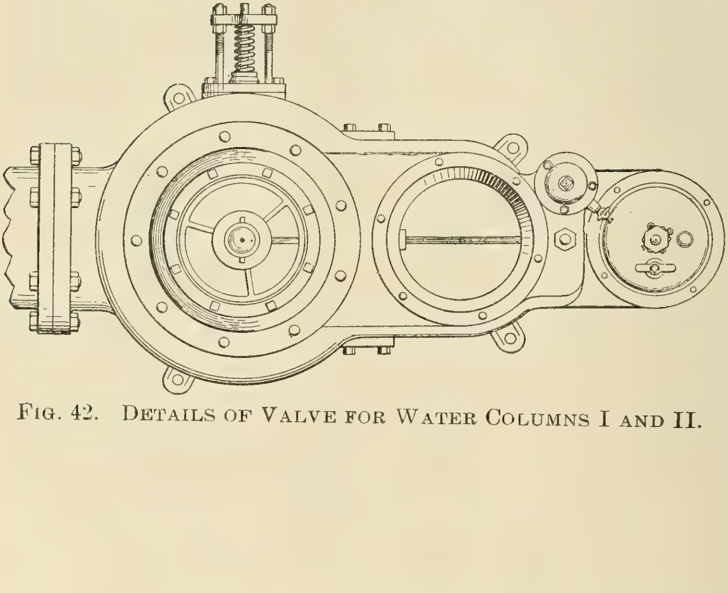


FIG. 42. DETAILS OF VALVE FOR WATER COLUMNS I AND II.

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TESTS OF NICKEL-STEEL RIVETED JOINTS

BY

ARTHUR N. TALBOT
AND
HERBERT F. MOORE

UNIVERSITY OF ILLINOIS
ENGINEERING EXPERIMENT STATION

URBANA, ILLINOIS
PUBLISHED BY THE UNIVERSITY

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UNIVERSITY OF ILLINOIS
ENGINEERING EXPERIMENT STATION

BULLETIN NO. 49 FEBRUARY 1911

TESTS OF NICKEL-STEEL RIVETED JOINTS

BY ARTHUR N. TALBOT, PROFESSOR OF MUNICIPAL AND SANITARY ENGINEERING AND IN CHARGE OF THEORETICAL AND APPLIED MECHANICS, AND HERBERT F. MOORE, ASSISTANT PROFESSOR IN THEORETICAL AND APPLIED MECHANICS

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TESTS OF NICKEL-STEEL RIVETED JOINTS.

I. INTRODUCTION.

1. *Preliminary.*—In designing riveted joints to connect structural members certain assumptions are made concerning the action of the rivets and other parts of the joint under load. Tests of riveted joints have not yet fully established the trustworthiness of some of these assumptions. In considering the design for a bridge across the St. Lawrence river near Quebec, Canada, to replace one which had failed during construction, the Board of Engineers of the Quebec Bridge appointed by the Canadian Government desired further experimental data on the action of riveted joints, especially as they had under consideration the use of nickel-steel plates and nickel-steel rivets; and arrangements were made by which tests were conducted at the University of Illinois. Later, the Pennsylvania Steel Company, of Steelton, Pennsylvania, arranged for similar tests of riveted joints made with chrome-nickel-steel plates and rivets. This bulletin records the results of the two series of tests. Although all material in the riveted joints tested contained nickel and the bulletin is termed Tests of Nickel-Steel Riveted Joints, in order to distinguish between the two sets the first set will be called nickel-steel riveted joints and the second set chrome-nickel-steel riveted joints.

The investigation included tests in tension and in alternate tension and compression. The bending of rivets, the deformation of the joints and the slip of the plates, the yield point of the joints, and the ultimate strength of the riveted joints were investigated. The tension tests included various forms of joint,–lap joints, butt joints, joints with fillers, joints with various numbers of rivets. The alternate tension and compression tests were upon one type of joint, a butt joint with very thick plates. A feature of interest was the repetitive loading of a joint alternately in tension and compression. The determination of the bending of the rivets was also a novel feature. The riveted joints which were tested in tension duplicated in dimensions a series of carbon-steel riveted joints tested for the American Railway Engineering and Maintenance of Way Association, and hence were not suited to develop the maximum strength possible with nickel-steel plates and rivets. To distinguish between the test pieces, the riveted joints of ordinary structural steel and ordinary rivets reported by the American Railway Engineering and Maintenance of Way Association will be called carbon-steel riveted joints; and those of the tests here recorded nickel-steel and chrome-nickel-steel riveted joints.

2. *The Strength of Riveted Joints.*—When a riveted joint is subjected to tension, tensile stresses are developed in the plates, bearing stresses in the rivets and in the plates at the rivet holes, shearing and bending stresses in the rivets, and shearing stresses in the plates beyond the rivet holes. Among the assumptions ordinarily made in the designing of riveted joints are: (a) that the tension and the tensile stresses are uniformly distributed throughout the width of the plate over the net section; (b) that the load is evenly divided among the rivets of the joint whether there are one or more rows and whether one row contains fewer rivets than another; (c) that little attention need be given to the relative amount of the stretch of the plate between the different rows of rivets; and (d) that the bearing area of a rivet is the product of its diameter (or the diameter of the hole) by the thickness of the plate in which it is placed. The limiting or safe shearing unit-stress in the rivet is ordinarily taken at two-thirds to three-fourths the limiting tensile unit-stress of the rivet material, and the bearing stress of the rivets, or of the plate, at one and one-third to one and one-half times this tensile stress. Under the assumed action of the joint, and considering the assumed limits of tensile, bearing, and shearing stresses, that stress which approaches most nearly to its assumed limit of stress at the load to be carried by the joint is considered to be the critical stress, whether this be the tensile stress in the net section of the plate, the bearing on the rivets, or the shearing stress in the various rivet sections. For any joint this critical stress will control the working strength of the joint; and whether it be tensile, bearing or shearing stress will depend upon the design of the joint and upon the ratios assumed between limiting or safe values of tensile stress, bearing stress and shearing stress.

For a given type of riveted joint the design in which the tensile stress, bearing stress, and shearing stress each reaches its limiting value, will have the highest efficiency, and a departure in proportions from this design will result in lowering the efficiency of the joint. However, matters connected with fabrication generally make modifications in design necessary—the size of rivet which may be handled with the facilities available, the size of hole which may properly be punched in the given thickness of metal, the closeness of spacing necessary to give tightness in joints subject to water or steam pressure, economies of workmanship, etc., will affect the design. Frequently empirical or conventional spacing or sizes of rivets are used. In any event the proper ratios of the allowable tensile, bearing, and shearing stresses may not be definitely known. The full action of the joint under load is uncertain. At the beginning of application of load the bearing may be on a small portion of the rivet surface. The rivet may not entirely fill the hole, and the shearing stress may not be uniformly distributed over the rivet section, or among all the rivets. Friction between plates by reason of the clamping action of the rivets may affect the distribution of stresses. Repetition of load may change the action of the joints and the amount of the stresses. Altogether, it is evident that fuller information on the action of riveted joints is necessary before the proper distribution of stresses may be judged. Conditions at rupture of the joint may not be applicable to working conditions, since stretch of plate, distortion of rivets, and the consequent redistribution of load beyond the yield point of the material may greatly change the action of the joint. It is evident that experimental data are needed to determine in detail the action of riveted joints under load.

3. *Existing Data.*—In the experimental study of the strength of riveted joints, the attention of English and American investigators has been directed largely to the resistance of joints to rupture; French, Dutch, and German investigators have given much attention to the frictional resistance to slip. Among European experiments those of Considere[1] in 1886, Dupuy[2], van der Kolk[3] in 1897, Bach[4] in 1894, and Pruess[5] in 1909, are worthy of special mention. The earlier of these investigators reported that the frictional hold of the rivets prevents slip in the joint up to loads slightly greater than those assumed in design practice for

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[1] Annales des Ponts et Chaussees, 1886.

[2] Annales des Ponts et Chaussees, 1895.

[3] Zeitschrift des Vereins Deutscher Ingenieure, June 26 and July 3, 1897. Le Genie Civil 1897. Practical Engineer, January 14, 1898, (Translation).

[4] Zeitschrift des Vereins Deutscher Ingenieure, 1892, p. 1142; 1894, p. 1231; 1895, p. 301.

[5] Iron and Steel Institute, Carnegie Scholarship Memoirs, Vol. 1 (1909), p. 60-95. In this memoir attention may be called to the fact that the shearing strength of specimens of rivet material (nickel steel) as given on page 76 should be divided by two, since the specimen is in double shear.

soft steel or wrought-iron plates and rivets. Considere, however, showed that if the frictional hold of the rivet is once broken the joint will afterwards slip under small loads if they are applied first in one direction and then in the other. In the experiments of Pruess (reported since the tests described in this bulletin were made) on joints having nickel-steel rivets, by the use of very sensitive extensometers, the existence of slip of joint was found at loads below those allowed in practice, and the test also showed that the use of nickel-steel rivets did not appreciably change the frictional hold of rivets on plates. All the European tests quoted above were made on joints in tension (with the exception of the few alternate stress tests of Considere) and, in general, were carried to rupture.

Among the English experiments may be mentioned those of Fairbairn[6], of Kirkaldy[7], and of Unwin and Kennedy[8]. In the experiments of Fairbairn and Kirkaldy the ultimate strength of the joint was studied. In the tests of Unwin and Kennedy a study was made of the effect of hand riveting and of hydraulic pressure riveting on both the ultimate strength and the frictional resistance of riveted joints.

In the United States the largest number of tests have been made at Watertown Arsenal[9]. In these tests deformation of joint was measured, but the efficiency of the joint was computed from the load carried at the ultimate.

In 1896 in the Laboratory of Applied Mechanics of the University of Illinois a series of tensile tests of riveted joints was made under the direction of A. N. Talbot by Van Ostrand and Thompson[10]. In these tests the slip of joint was found to begin at loads as low as those allowed in practice, and the effect of bending of rivet and of unequal distribution of stress in bearing of rivet and in shear was investigated.

In 1904 a series of tests on riveted joints in tension was carried on under the auspices of the Committee on Iron and Steel Structures of the American Railway Engineering and Maintenance of Way Association. The tests were made in the laboratory of the College of Civil Engineering of Cornell University[11]. In these tests the deformation of joint under load, the slip of the joint, and the permanent set of joint after load were measured, and the strength of joints with filler plates between main plates and cover plates was compared with that of joints without filler plates. These tests also showed the existence of slip at working loads.

---

[6] Proceedings of the (British) Institution of Mechanical Engineers, April, 1881.

[7] American Machinist, May 11 and 18, 1893 (Condensed report of Kirkaldy's tests).

[8] Proceedings of the (British) Institution of Mechanical Engineers, 1881, 1882 and 1885.

[9] Tests of Metals (Watertown Arsenal Reports) 1885, 1886, 1887, 1896 and other volumes.

[10] Thesis of Van Ostrand and Thompson, 1896 (University of Illinois Library).

[11] Proceedings of the American Railway Engineering and Maintenance of Way Association, 1905, Vol. 6.

4. *Acknowledgment.*—The tests of nickel-steel riveted joints were undertaken at the request of the Board of Engineers of the Quebec Bridge, Messrs. H. E. Vautelet of Montreal, Maurice Fitzmaurice of London, England, and Ralph Modjeski of Chicago. The nickel-steel riveted joints were designed and furnished by the Board of Engineers and were manufactured under their inspection. Especial acknowledgment should be made to Mr. Ralph Modjeski for his suggestions and advice during the course of the work. The tests of chrome-nickel-steel riveted joints were undertaken at the request of the Pennsylvania Steel Company, the riveted joints following in form and dimensions the riveted joints tested for the Board of Engineers of the Quebec Bridge. Both the Board of Engineers of the Quebec Bridge and the Pennsylvania Steel Company agreed to the publication of the results of the tests by the Engineering Experiment Station of the University of Illinois. The expense of the tests was largely borne by the Board of Engineers and the Pennsylvania Steel Company.

The designing of the special auxiliary apparatus necessary for the tests and the work of testing was done by the research force of the Laboratory of Applied Mechanics of the University of Illinois. The chemical analyses of plate and rivet material were made in the laboratories of the Department of Applied Chemistry of the University of Illinois.

II. MATERIALS, TEST PIECES, AND METHOD OF TESTING.

5. *Materials.*—The plates of the joints included in this investigation were nickel steel and chrome nickel steel. In Table 1 are given the results of analyses of the steel. The carbon content and the manganese content were determined by colorimetric methods. Physical tests of several samples from different plates were made, and the results of these tests are given in Table 2.

The rivets were nickel steel and chrome nickel steel. The results of analyses of sample rivet material furnished by the Pennsylvania Steel Company as representative of the rivets used in making the joints are given in Table 1. Physical tests of this

TABLE 1.

CHEMICAL COMPOSITION OF RIVET AND PLATE MATERIAL.

Element	Nickel-steel Riveted Joints		Chrome-nickel-steel Riveted Joints	
	Rivet Material per cent	Plate Material per cent	Rivet Material per cent	Plate Material per cent
Carbon*	0.141	0.258	0.136	0.191
Sulphur	0.0023	0.008	0.038	0.035
Phosphorus	0.037	0.044	0.032	0.042
Manganese*	0.442	0.700	0.696	0.485
Nickel	3.33	3.330	0.986	0.733
Chromium	......	.....	0.240	0.170

*The carbon content and the manganese content were determined by colorimetric methods.

TABLE 2.

PHYSICAL PROPERTIES OF RIVET AND PLATE MATERIAL.

All stresses are given in pounds per square inch.

Item	Nickel-Steel		Chrome-Nickel-Steel	
	Rivet Material	Plate Material	Rivet Material	Plate Material
Number of specimens tested	2	9	2	8
Stress at first noticeable set*	......	38 200	.....	29 100
Stress at limit of proportionality of stress to deformation*	......	40 200	......	27 200
Stress at yield point†	45 000	51 700	38 400	36 300
Stress at ultimate	68 500	89 700	59 000	63 900
Elongation in 2 inches, per cent†	33.5	25.0	35.2	31.7
Reduction of area, per cent	63.4	55.8	63.3	59.9
Modulus of elasticity*	......	29 950 000	......	30 750 000

*Determined from tensile tests of threaded-end specimens with 8-inch gauge length.
†Determined from tensile tests of threaded-end specimens with 2-inch gauge length.

rivet material were made, and the results of these tests are given in Table 2. A special series of tensile tests of flat specimens cut from plates of the chrome-nickel-steel riveted joints was made. Half of these specimens were tested at the Laboratory of Applied Mechanics of the University of Illinois and half at

Watertown Arsenal. Table 3 shows the principal results of these tests.

6. *Test Pieces.*—The form and dimensions of the riveted joints are shown in Fig. 1, 2, 3, 4, and 5. The joints tested in tension had the same form and dimensions as did the carbon-steel riveted joints in the series of tests made by the Maintenance of Way Association, which was noted on page 6, as the Board of Engineers desired, among other results, a comparison of the strength of carbon-steel and nickel-steel riveted joints. Fig. 5 shows the form and dimensions of the test joints used in the tests made under alternate tension and compression. The plates were made thick to avoid buckling under compression.

TABLE 3.

TENSILE TESTS OF FLAT SPECIMENS OF CHROME-NICKEL STEEL.

Item	University of Illinois Tests	Watertown Arsenal Tests
Number of specimens tested	6	6
Stress at yield point pounds per square inch..	36 500	36 800
Stress at ultimate pounds per square inch..	60 000	61 000
Elongation, per cent........	27.3*	27.1†
Reduction of area, per cent..	54.0	51.9

* Gauge length eight inches.

† Gauge length six inches.

The joints were fabricated by the Pennsylvania Steel Company at their works at Steelton, Pennsylvania. An effort was made to have the quality of the riveting representative of high-grade commercial work—made neither too well nor too poorly. The nickel-steel test pieces were made under the inspection of one of Mr. Modjeski's inspectors, acting for the Board of Engineers of the Quebec Bridge; and the inspector rejected some joints as being more tightly riveted than could be expected under ordinary conditions of structural practice. The Pennsylvania Steel Company gave their own supervision in the making of the chrome-nickel-steel test pieces.

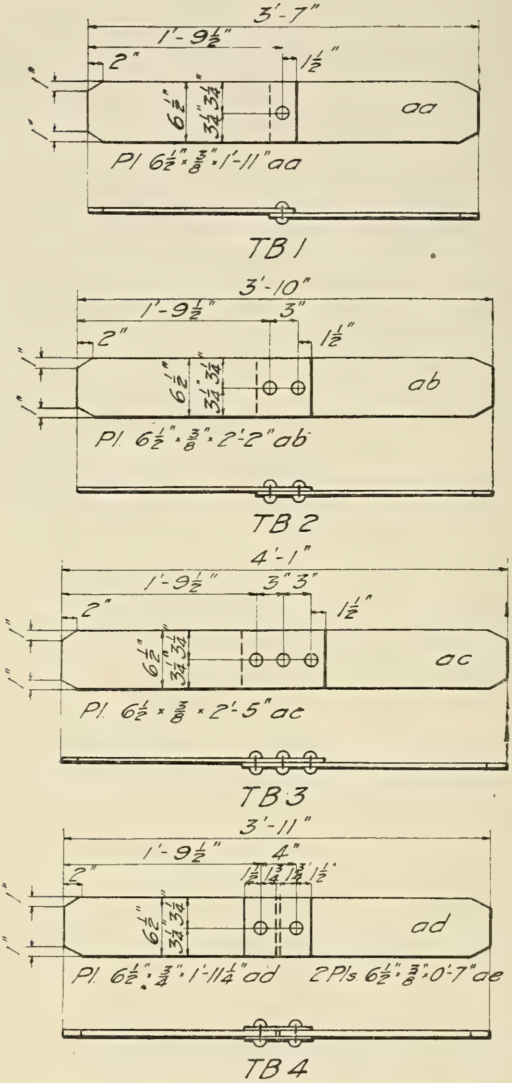


FIG. 1. RIVETED JOINT TEST PIECES.

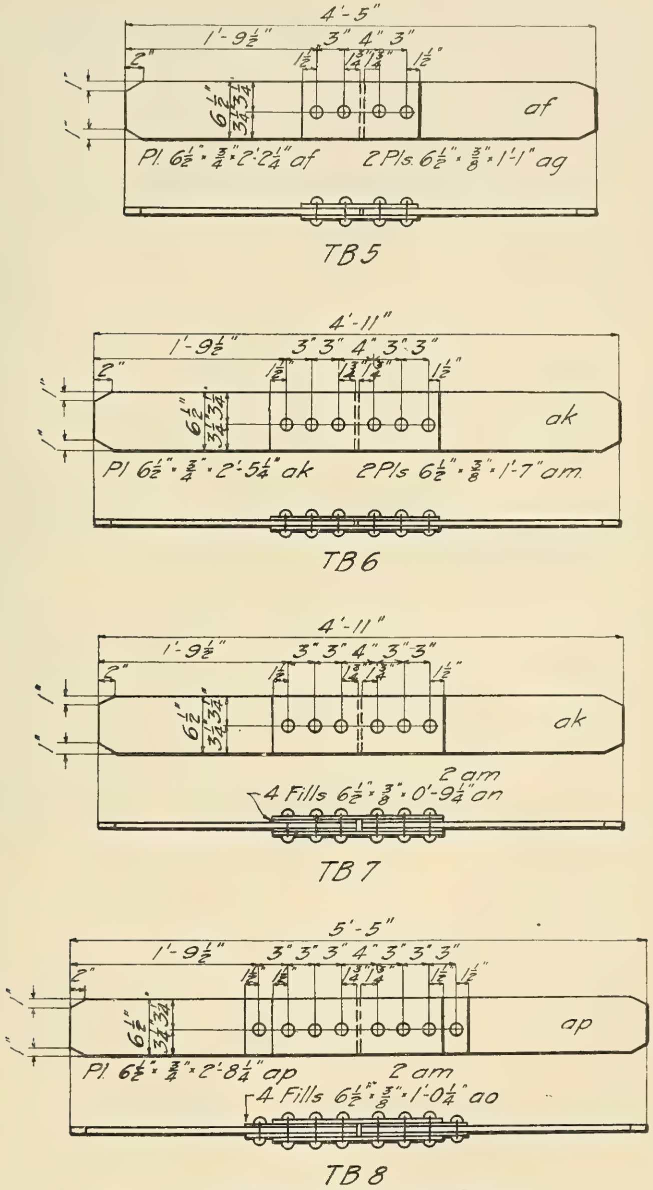


FIG. 2. RIVETED JOINT TEST PIECES.

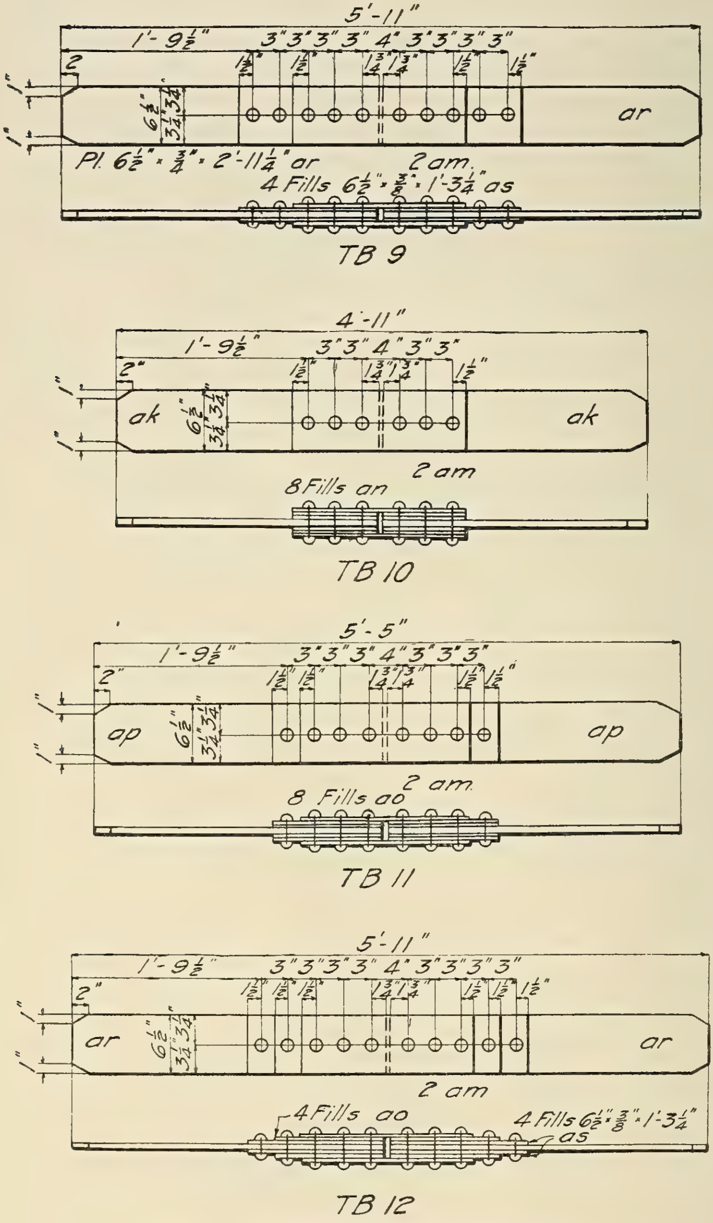


FIG. 3. RIVETED JOINT TEST PIECES.

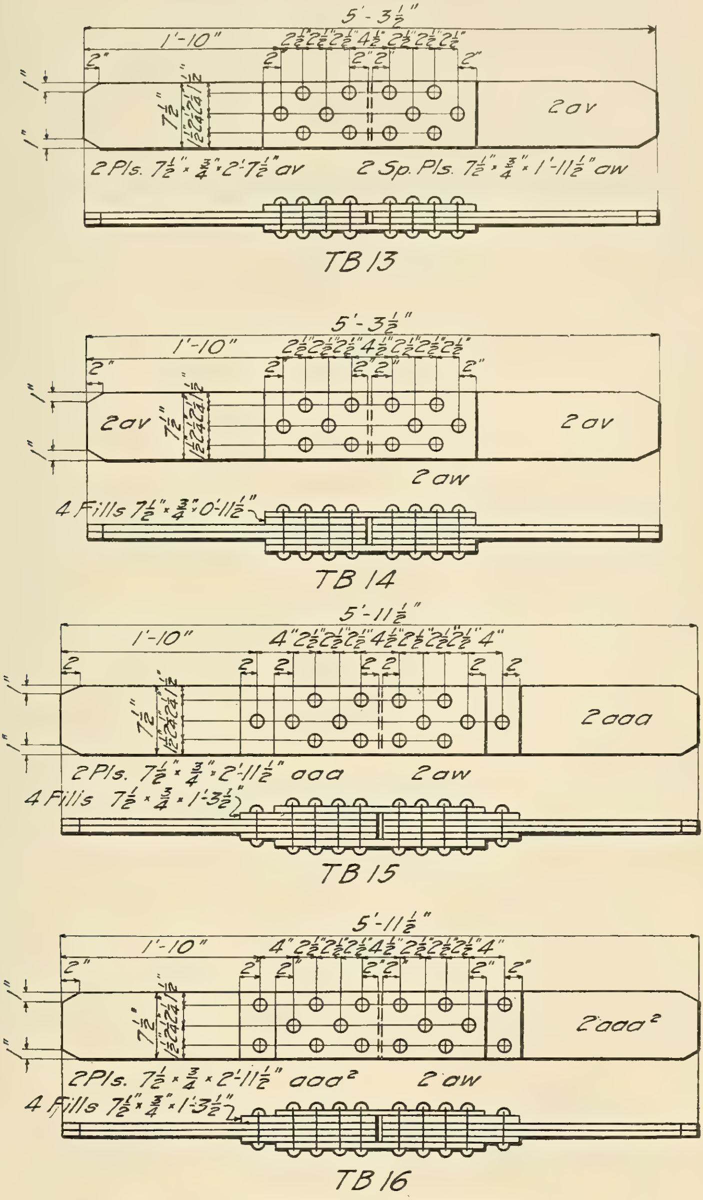
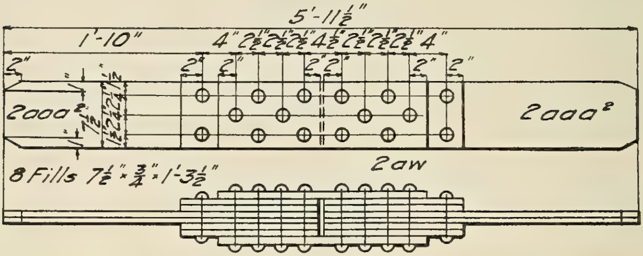
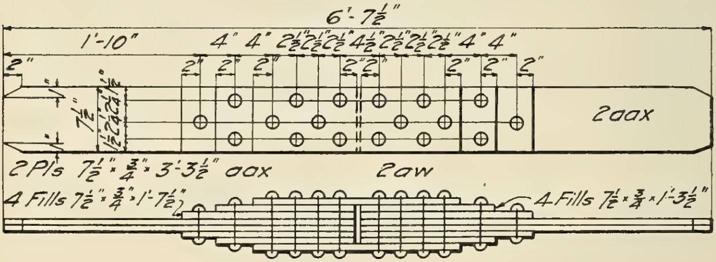

5'-3½"
1'-10"
2av
2 Pls. 7½" × ¾" × 2'-7½" av
2 Sp. Pls. 7½" × ¾" × 1'-11½" aw
TB 13
5'-3½"
1'-10"
2av
2av
2aw
4 Fills 7½" × ¾" × 0'-11½"
TB 14
5'-11½"
1'-10"
2aaa
2 Pls. 7½" × ¾" × 2'-11½" aaa
2aw
4 Fills 7½ × ¾ × 1'-3½"
TB 15
5'-11½"
1'-10"
2aaa²
2 Pls. 7½ × ¾ × 2'-11½" aaa²
2aw
4 Fills 7½" × ¾" × 1'-3½"
TB 16

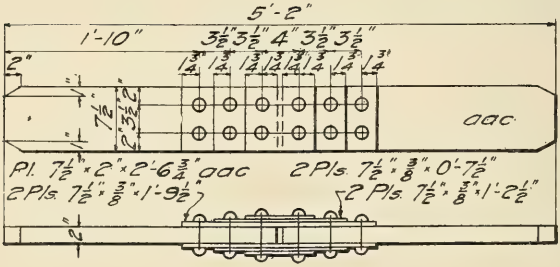
FIG. 4. RIVETED JOINT TEST PIECES.



TB 17



TB 18



TB 19, 20, 21, 22.

FIG. 5. RIVETED JOINT TEST PIECES.

TABLE 4.

CLASSIFICATION OF TEST JOINTS.

All rivets were ⅞ inch in diameter. All surfaces in contact were painted with one coat of graphite paint. Joints designated as shop-riveted were riveted with a hydro-pneumatic riveting machine; those designated as field-riveted joints were riveted by a hand pneumatic hammer.

Joint	Material of Plates and Rivets	Number of Joints Tested	Method of Riveting	Number of Rivets Sheared	Single or Double Shear	Cross section of Main Plates inches	Filler Plates Each Side	Remarks
TB1S	Ni. Steel	3	Shop	1	Single	6½x⅜	None	Tested in tension
TB1F	“	2	Field	1	“	“	“	“
TB1L	Cr.Ni.Steel	3	Shop	1	“	“	“	“
TB2S	Ni. Steel	3	Shop	2	Single	6½x⅜	None	Do
TB2F	“	2	Field	2	“	“	“	“
TB2L	Cr.Ni.Steel	3	Shop	2	“	“	“	“
TB3S	Ni. Steel	3	Shop	3	Single	6½x⅜	None	Do
TB3F	“	2	Field	3	“	“	“	“
TB3L	Cr.Ni.Steel	3	Shop	3	“	“	“	“
TB4S	Ni. Steel	3	Shop	1	Double	6½x¾	None	Do
TB4F	“	2	Field	1	“	“	“	“
TB4L	Cr.Ni.Steel	3	Shop	1	“	“	“	“
TB5S	Ni. Steel	3	Shop	2	Double	6½x¾	None	Do
TB5F	“	2	Field	2	“	“	“	“
TB5L	Cr.Ni.Steel	3	Shop	2	“	“	“	“
TB6S	Ni. Steel	3	Shop	3	Double	6½x¾	None	Do
TB6F	“	2	Field	3	“	“	“	“
TB6L	Cr.Ni.Steel	3	Shop	3	“	“	“	“
TB7S	Ni. Steel	3	Shop	3	Double	6½x¾	One	Do
TB7F	“	2	Field	3	“	“	“	“
TB7L	Cr.Ni.Steel	3	Shop	3	“	“	“	“
TB8S	Ni. Steel	3	Shop	3	Double	6½x¾	One	Tested in tension Filler anchored with 1 rivet
TB8F	“	2	Field	3	“	“	“	
TB8L	Cr.Ni.Steel	3	Shop	3	“	“	“	
TB9S	Ni. Steel	3	Shop	3	Double	6½x¾	One	Tested in tension Filler anchored with 2 rivets
TB9F	“	2	Field	3	“	“	“	
TB9L	Cr.Ni.Steel	3	Shop	3	“	“	“	
TB10S	Ni. Steel	3	Shop	3	Double	6½x¾	Two	Tested in tension
TB10F	“	2	Field	3	“	“	“	“
TB10L	Cr.Ni.Steel	3	Shop	3	“	“	“	“
TB11S	Ni. Steel	3	Shop	3	Double	6½x¾	Two	Tested in tension Fillers anchored with 1 rivet
TB11F	“	2	Field	3	“	“	“	
TB11L	Cr.Ni.Steel	3	Shop	3	“	“	“	
TB12S	Ni. Steel	3	Shop	3	Double	6½x¾	Two	Tested in tension Fillers anchored with 2 rivets
TB12F	“	2	Field	3	“	“	“	
TB12L	Cr.Ni.Steel	3	Shop	3	“	“	“	
TB13S	Ni. Steel	3	Shop	6	Double	7½x¾*	None	Tested in tension
TB13F	“	2	Field	6	“	“ *	“	
TB13L	Cr.Ni.Steel	3	Shop	6	“	“ *	“	“
TB14S	Ni. Steel	3	Shop	6	Double	7½x¾*	One	Do
TB14F	“	2	Field	6	“	“ *	“	“
TB14L	Cr.Ni.Steel	3	Shop	6	“	“ *	“	“
TB15S	Ni. Steel	3	Shop	6	Double	7½x¾*	One	Tested in tension Fillers anchored with 1 rivet
TB15F	“	2	Field	6	“	“ *	“	
TB15L	Cr.Ni.Steel	3	Shop	6	“	“ *	“	
TB16S	Ni. Steel	3	Shop	6	Double	7½x¾*	One	Tested in tension Fillers anchored with 2 rivets
TB16F	“	2	Field	6	“	“ *	“	
TB16L	Cr.Ni.Steel	3	Shop	6	“	“ *	“	

* Double plates.

TABLE 4.—(*Continued.*)

Joint	Material of Plates and Rivets	Number of Joints Tested	Method of Riveting	Number of Rivets Sheared	Single or Double Shear	Cross Section of Main Plates inches	Filler Plates Each Side	Remarks
TB17S	Ni. Steel	3	Shop	6	Double	7½x¾*	Two	Tested in tension Fillers anchored with 2 rivets
TB17F	"	2	Field	6	"	" *	"	
TB17L	Cr.Ni.Steel	3	Shop	6	"	" *	"	
TB18S	Ni. Steel	3	Shop	6	Double	7½x¾*	Two	Tested in tension Fillers anchored with 3 rivets
TB18F	"	2	Field	6	"	" *	"	
TB18L	Cr.Ni.Steel	3	Shop	6	"	" *	"	
TB19S	Ni. Steel	2	Shop	6	Double	7½x2	None	For tests in alternate tension and compression
TB20S	"	2	"	6	"	"	"	
TB21S	"	2	"	6	"	"	"	
TB22S	"	2	"	6	"	"	"	
TB19F	Ni. Steel	2	Field	6	Double	7½x2	None	Do.
TB20F	"	2	"	6	"	"	"	"
TB21F	"	2	"	6	"	"	"	"
TB22F	"	2	"	6	"	"	"	"
TB19L	Cr.Ni.Steel	4	Shop	6	Double	7½x2	None	Do.
TB20L	"	4	"	6	"	"	"	"
TB21L	"	4	"	6	"	"	"	"
TB22L	"	4	"	6	"	"	"	"

* Double plates.

Table 4 gives a classification of the test joints with a tabulation of their principal dimensions. In all 176 joints were tested. For the nickel-steel joints five or more specimens of each type were tested and of each type some were riveted with a hydro-pneumatic riveter and others were riveted with a hand pneumatic hammer. Joints riveted with the hydro-pneumatic riveter were marked S and are hereafter referred to as shop-riveted joints. Joints riveted with a hand pneumatic hammer were marked F and are hereafter referred to as field-riveted joints. All chrome-nickel-steel joints were riveted with a hydro-pneumatic riveter. They were marked L. In all test joints the surfaces in contact had been given one coat of graphite paint.

Only one type of joint was tested under alternate tension and compression (see Fig. 5). There were thirty-two joints of this type.

7. *Testing Machine and Its Arrangement.*—The tension tests were made in the 600 000-lb. screw-power Riehle testing machine of the Laboratory of Applied Mechanics of the University of Illinois. The ends of the specimens were held in the heads of the machine by wedge-shaped grips. In testing, the load was applied at a speed of head of machine of 0.4 in. per min.

The thirty-two joints designed to withstand alternate tension and compression were also tested in the 600 000-lb. testing machine. In the tests in alternate tension and compression, the machine was fitted with an auxiliary cross-head and with two auxiliary nuts on the screws. Fig. 6 shows in diagram the arrangement of apparatus, and Fig. 7 shows the general appearance of the machine fitted with the auxiliary apparatus.

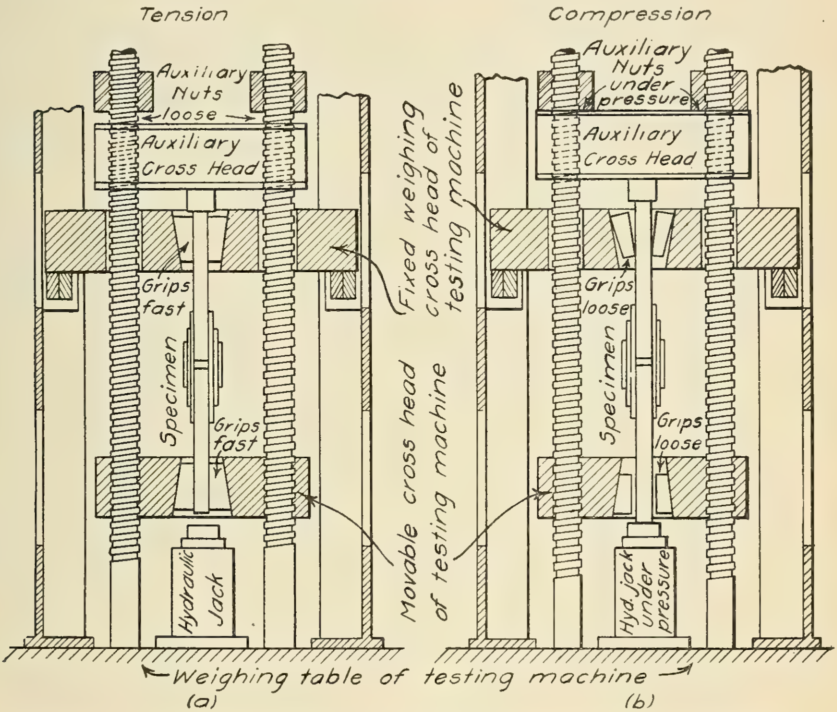


FIG. 6. AUXILIARY APPARATUS FOR TESTS IN ALTERNATE TENSION AND COMPRESSION.

Tension and compression were applied alternately as follows: To put the specimen in tension the load was applied through the screws of the machine and weighed in the usual manner. During this part of the test the auxiliary cross-head above the weighing head of the testing machine rested on the top of the specimen, and the auxiliary nuts were clear of the auxiliary cross-head and turned with the screws. (See Fig. 6 (a)). The specimen, of course, was held by the wedge grips. The tension load was next released, after which the lower grips loosened themselves from the specimen. The hydraulic jack under the specimen was then pumped up, and its rising plunger carried the specimen and the auxiliary cross-head upward until the auxiliary cross-head was forced against the auxiliary nuts and the specimen put in compression. Fig. 6 (b) shows this condition. The reaction of the hydraulic jack on the weighing table was weighed by balancing the beam of the testing machine, and, of course, was equal to the compression load on the specimen. The pressure was next released from the jack, the weight of the auxiliary cross-head acted to tighten the grips in the weighing head of the machine, the lower grips were tightened by hand, and another tension load was applied. It will be seen that the load in compression was as accurately determined as that in tension.

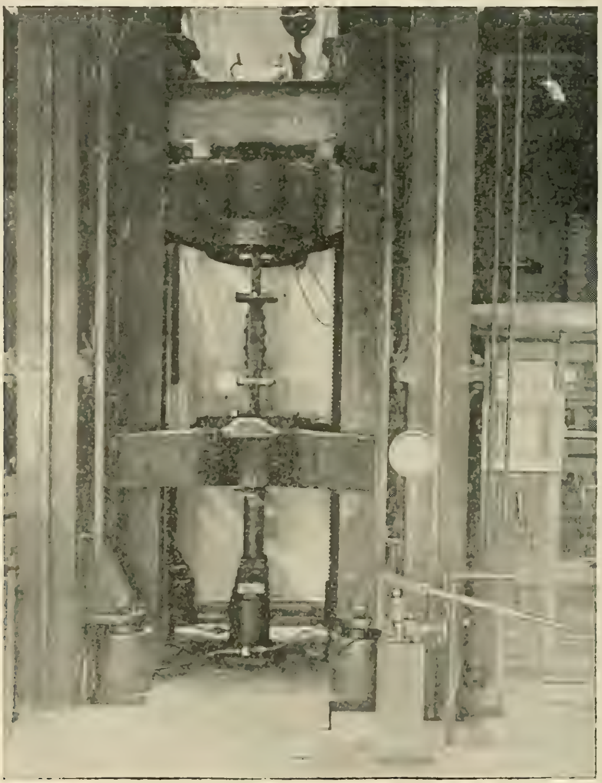


FIG. 7. VIEW OF TESTING MACHINE WITH AUXILIARY APPARATUS FOR TESTS IN ALTERNATE TENSION AND COMPRESSION.

8. *Measurement of Deformation.*—In the tension tests the elongation of the specimen was measured by means of the apparatus shown in Fig. 8. This instrument consists of two frames AA_1 which are fastened to the specimen by pointed screws SS_1, these screws being symmetrically placed with respect to the longitudinal axis of the specimen. As the specimen stretches, the frames tend to separate, but at the right hand side (as shown in the figure) they are held at a constant distance apart by means of the rod R, whose ends receive the pivots FF, and by the springs XX. At the left hand side the lower frame carries a dial D around which rotates a pointer. On the axle of this pointer is a small sheave one inch in circumference, which is driven by a fine insulated copper wire wrapped around it. This wire, which is kept taut by the weight W, is attached at its upper end to the pin P which is carried at the left hand side of the upper frame. This wire and the axis of the rod R are equidistant from the axis of

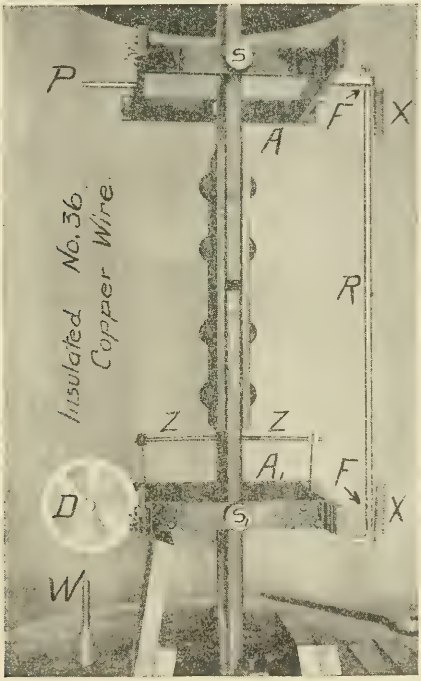


FIG. 8. VIEW OF EXTENSOMETER ATTACHED TO TEST PIECE.

the specimen, and thus as the specimen stretches, the pin P and the dial D separate by twice the stretch of the specimen, and this double stretch is indicated by the pointer on the dial. The dial was graduated to measure the stretch of the piece to one ten-thousandth of an inch. Before making tests with this apparatus, the dial wrapped with wire was tested in comparison with a screw micrometer, and it was found under repeated reversals to be free from slip of wire over drum and free from appreciable error. The apparatus behaved with entire satisfaction during the test and, it is believed, gave thoroughly trustworthy results.

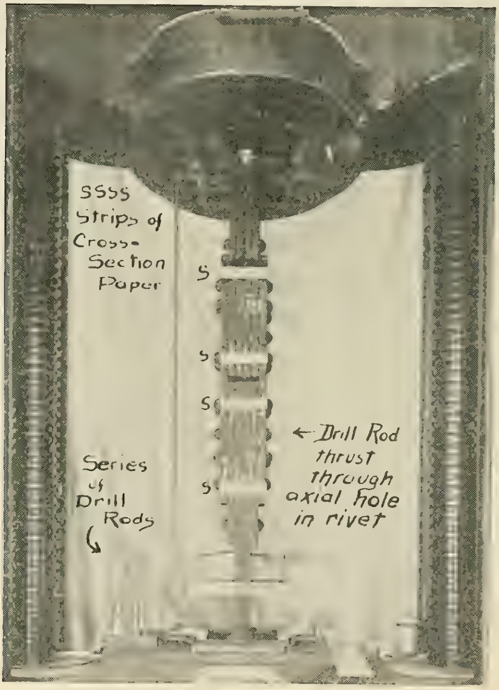

SSSS Strips of Cross-Section Paper
S
S
S
S
← Drill Rod thrust through axial hole in rivet
Series of Drill Rods

FIG. 9. VIEW OF TENSION TEST PIECE WITH AUXILIARY APPARATUS FOR MEASURING DEFORMATION.

For the purpose of measuring the movement of the several plates of a joint, strips of cross-section paper were glued across the narrow sides of the plates before testing the joints, and after the glue had hardened, these strips were cut into pieces along the edges of the plates, leaving a piece attached to each plate. As the plates slipped over each other the amount of slip was read directly from the cross-section paper. Fig. 9 and 10 show this arrangement.

In the tests in alternate tension and compression the same apparatus was used to measure the deformation of the joints as was used in the tension tests.

In one or more joints of each type the bending of the rivets was investigated. The apparatus used for detecting the bending of rivets is shown in Fig. 9 and 11. Holes 0.204 inch in diameter were drilled through all rivets of the joint as nearly axially as possible. A series of Stubs' steel drill rods varying in diameter from 0.180 inch to 0.204 inch by steps of about 0.003 inch was provided, and under the initial load the largest drill rod which could be thrust through the hole was determined by trial. This arrangement is illustrated in Fig. 11 (a) where d_1 is the diameter of this drill rod. Under any other load on the joint, if appreciable bending of the rivet had occurred, this drill rod could not be thrus

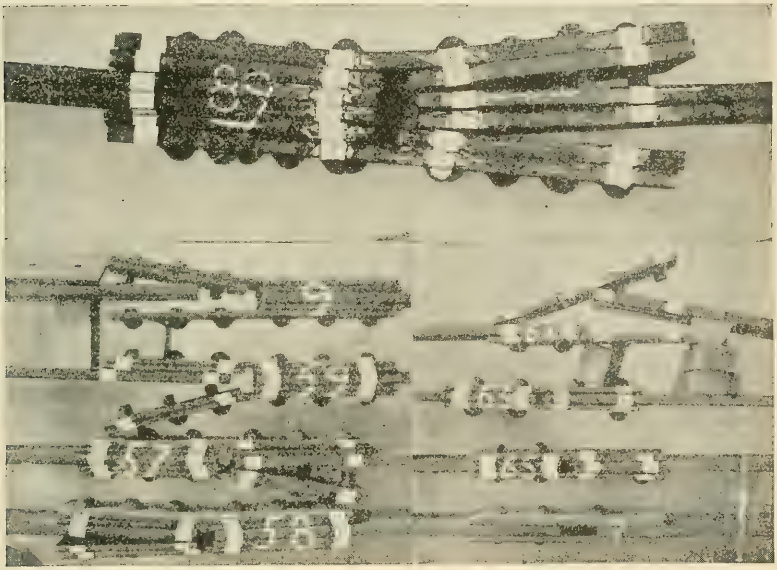


FIG. 10. VIEW OF FRACTURED TEST PIECES SHOWING MOVEMENT OF PLATES.

through the hole in the rivet, and the maximum size of rod which would pass the hole was of smaller diameter (d_2), as illustrated in Fig. 11 (b). $d_1 - d_2$ gives the total amount of bending and detrusion under the given load.

9. *Procedure of Tests.*—In the tension tests an initial load of 1000 lb. was first applied, and the dial of the extensometer set to zero; the first desired load was then applied and the dial read; the load was then reduced to the initial load of 1000 lb. and the dial again read; the next higher load was then applied, and the load again reduced to the initial load. This process was repeated until a load equal to about three-quarters of the estimated breaking load had been applied. At this point the measuring instrument was removed, and in the further test the load was progressively applied to failure, the reading of the cross-section paper being taken at intervals throughout the entire test.

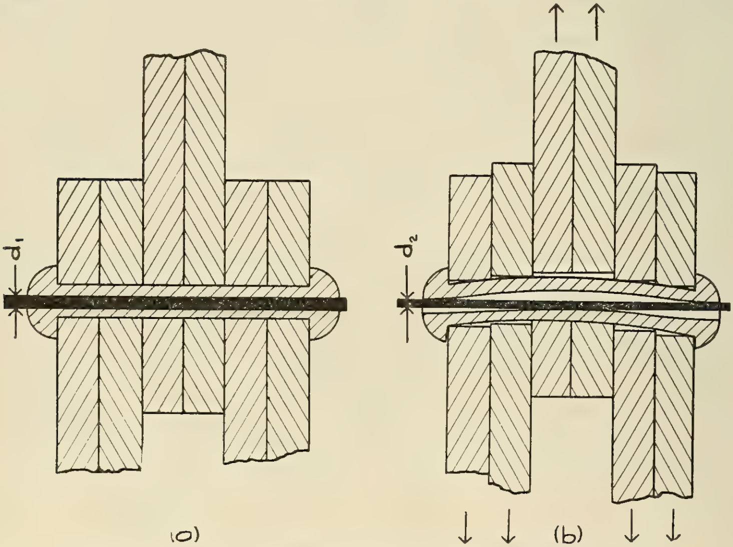


Fig. 11. Diagram Showing Method of Measuring Bending of Rivets.

In the tests of the joints designed to withstand alternate tension and compression (sixteen joints of nickel-steel and sixteen joints of chrome-nickel-steel of the form and dimensions shown in Fig. 5), the following schedule was carried out:

(a) Six specimens tested in tension, with release of load and observation of deformation and set as the load was progressively increased. (Joints TB20L, TB21L, TB20L, TB20S, TB21S, and TB22F).

(b) Six specimens tested in compression, with release of load and observations of deformation and set as the load was progressively increased. (Joints TB19L, TB20L, TB22L, TB22S, TB20F, and TB22F).

(c) Six specimens tested in alternate tension and compression, a tension load being first applied followed by an equal load in compression, then an increased load applied in tension followed by an equal load in compression, etc., the joint being finally broken in tension. (Joints TB22L, TB22L, TB22L, TB20F, TB21S, and TB19S).

(d) Four specimens tested as in (c), and in addition the bending of the rivets was investigated by the aid of holes drilled through them. (Joints TB21L, TB20L, TB21F, TB19F).

(e) Four specimens tested as in (c), except that the compression load applied was only one-half of the preceding tension load. (Joints TB19L, TB19L, TB20S, and TB22S).

(f) Two specimens tested as in (c), except that in all but the higher loads the cycle of tension and compression for any given load was repeated five times before the next larger load was applied. (Joints TB19L and TB20S).

(g) Four specimens tested by repeatedly applying alternately in tension and compression a load producing a rivet shear of about 10 000 lb. per sq. in., and occasionally interjecting a single application of a higher load. (Joints TB21L, TB21L, TB19F, and TB21F).

During the application and release of a load, throughout the above schedule, observations of deformation were taken at several loads, in order that the stress-deformation diagram of the specimen might be plotted during the application of tension, the release of tension, the application of compression, and the release of compression, i. e., throughout the complete cycle of stress.

In all tests in the second series except tests 69, 70, 105 and 106 the increment of load was 25 000 lb. In nearly all cases the maximum load applied before removing the measuring instruments was 300 000 lb. After the removal of the instruments a higher load was applied and the piece was broken. In tests 69, 70, 105 and 106 ((g) in the schedule of tests) the method of procedure was as follows: The specimen was subjected to ten cycles of alternated loading, the load both in tension and compression being such as to produce a shearing stress of about 10 000 lb. per sq. in.

in the rivets. The specimen was then subjected to one cycle of stress at loads which gave a shearing stress of about 15 000 lb. per sq. in. in rivets. Then followed ten cycles with 10 000 lb. per sq. in. shear in rivets, then one cycle with 20 000 lb. per sq. in., then ten cycles with 10 000 lb. per sq. in., then one cycle with 25 000 lb. per sq. in., and finally one cycle with 10 000 lb. per sq. in. After this the piece was broken in tension.

III. Data and Discussion.

10. *Sample Data of Tension Tests.*—Table 5, page 25, gives the data of a sample tension test of the riveted joints, (Joint TB10S, Test 83). In this particular test the bending of the rivets was investigated by means of the device already described. The data are self-explanatory. Fig. 12 shows the plotted data of this test. The lines drawn solid show deformation under stress and the lines drawn broken show permanent set after removal of stress. Complete data for all tests and curves for each test piece are on file in the Laboratory of Applied Mechanics of the University of Illinois, but in general only summarized data will be given in this bulletin.

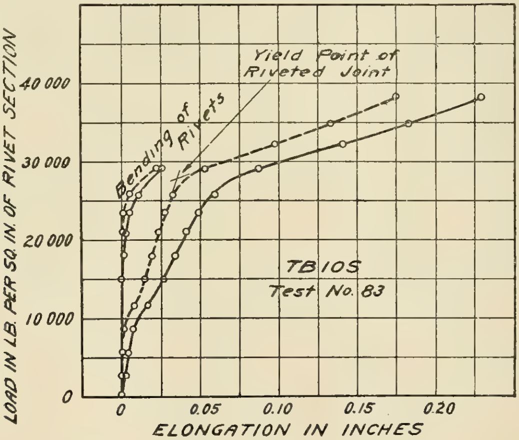


Fig. 12. Diagram of Test No. 83.

11. *Sample Data of Tension and Compression Tests.*—Table 6, page 27, shows the data of a sample test of a riveted joint under alternate tension and compression, (Joint TB21F, Test 94). In this test the bending of the rivets was investigated. Fig. 13 has been plotted from the data. In this test loads in tension were

followed by equal loads in compression. Fig. 14 shows the plotted results of a test in which loads in tension were followed by half as great loads in compression. Fig. 15 (Joint TB21L) shows the plotted results of a test under stress in tension only; a diagram of a test in compression only would be quite similar in appearance.

TABLE 5.

Sample Data of Tension Test of Riveted Joint.

Shear per square inch of rivet is based on the shearing area computed from the nominal diameter of rivet—⅞ inch.

Specimen TB10S. Test No. 83.

Load pounds	Shear per square in. of rivet pounds	Extensometer Gauge Length 30 in.		Drill Number of Largest Rod through Rivet. Holes 0.204 in. in Diameter.					
		Elongation inches	Set inches						
1 000	290		0.0000	8	7	8	8	8	8
9 600	2 810	.0025		8	7	8	8	8	8
1 000	290		.0000	8	7	8	8	8	8
19 500	5 710	.0042		8	7	8	8	8	8
1 000	290		.0005	8	7	8	8	8	8
30 200	8 820	.0075		8	7	8	8	8	8
1 000	290		.0015	8	7	8	8	8	8
40 000	11 720	.0168		8	7	8	8	8	8
1 000	290		.0079	8	7	8	8	8	8
51 200	15 000	.0260		8	7	8	8	8	8
1 000	290		.0146	8	7	8	8	8	8
61 500	18 000	.0337		8	8	8	8	8	8
1 000	290		.0192	8	7	8	8	8	8
71 800	21 040	.0409		9	8	8	8	8	8
1 000	290		.0234	8	8	8	8	8	8
80 400	23 550	.0495		9	8	9	9	8	9
1 000	290		.0272	8	8	8	8	8	8
87 700	25 680	.0588		11	11	11	9	9	11
1 000	290		.0325	9	9	9	8	8	9
99 600	29 160	.0875					13	12	14
1 000	290		.0531	14	13	14	11	11	12
109 800	32 150	.1410							
1 000	290		.0978						
119 400	34 920	.1823							
1 000	290		.1335						
128 800	37 700	.2286							
1 000	290		.1750						
182 200	53 320	Maximum load							

Upper rivets on north side sheared between second filler and main plate.

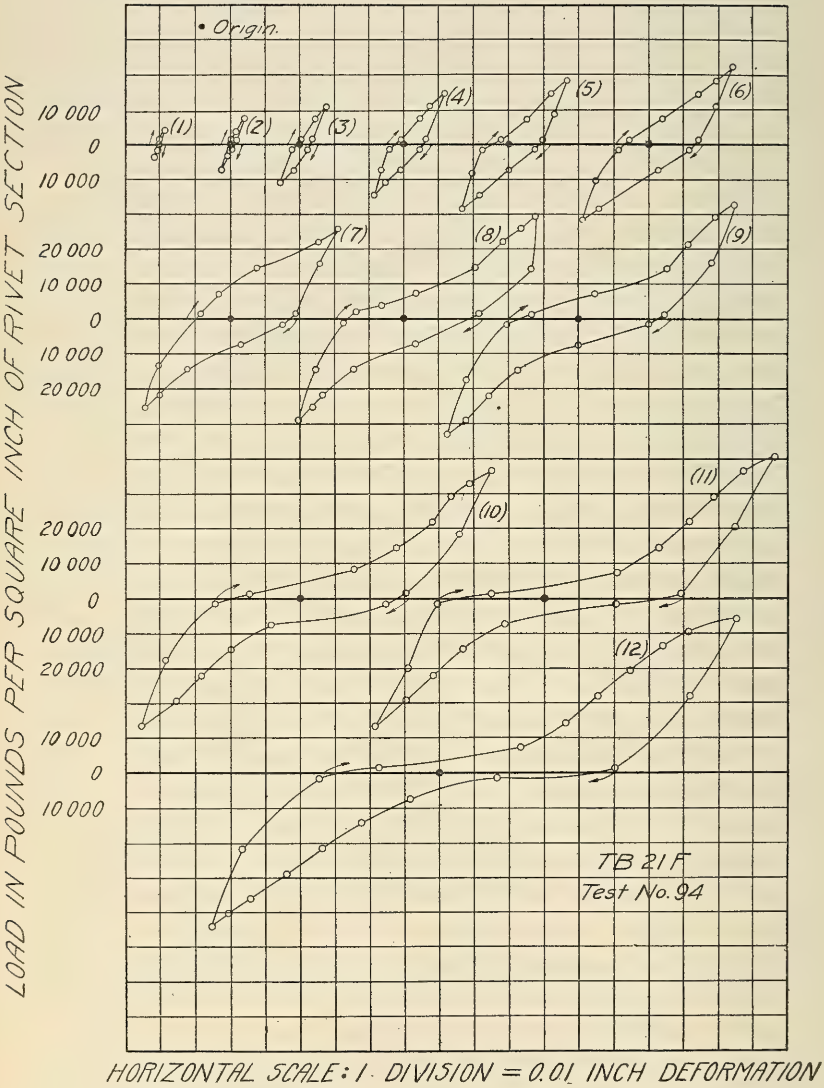


FIG. 13. DIAGRAM OF TENSION AND COMPRESSION TEST NO. 94.

TABLE 6.

SAMPLE DATA OF TEST OF RIVETED JOINTS IN ALTERNATE TENSION AND COMPRESSION.

T denotes load in tension; C, load in compression. Shear per square inch of rivet is based on the shearing area computed from the nominal diameter of rivet—⅞ inch.

Specimen TB21F. Test No. 94.

Load pounds	Shear per Square Inch of Rivet. pounds	Elongation in 20 Inches	Drill Number of Largest Rod through Rivet. Holes 0.204 in. in Diameter
T 7 000	1 025	+.0000	6 6 6 6 6 6
T 28 000	4 100	+.0014	6 6 6 6 6 6
T 7 000	1 025	+.0007	
C 10 000	1 465	—.0007	
C 25 000	3 665	—.0014	
C 10 000	1 465	—.0007	
T 7 000	1 025	+.0003	
T 25 000	3 665	+.0016	
T 50 000	7 330	+.0041	6 6 6 6 6 6
T 7 000	1 025	+.0020	
C 10 000	1 465	+.0005	
C 25 000	3 665	—.0005	
C 50 000	7 330	—.0025	6 6 6 6 6 6
C 10 000	1 465	—.0009	
T 7 000	1 025	+.0004	
T 50 000	7 330	+.0044	
T 75 000	10 990	+.0075	
T 7 000	1 025	+.0037	
C 10 000	1 465	+.0021	
C 50 000	7 330	—.0016	
C 75 000	10 990	—.0054	6 6 6 6 6 6
C 10 000	1 465	—.0023	
T 7 000	1 025	– .0008	
T 50 000	7 330	+.0047	
T 75 000	10 990	+.0075	
T 100 000	14 650	+.0118	6 6 6 6 6 6
T 7 000	1 025	+.0062	
C 10 000	1 465	+.0044	
C 50 000	7 330	—.0010	
C 75 000	10 990	—.0052	
C 100 000	14 650	—.0088	6 6 6 6 6 6
C 51 000	7 475	—.0068	
C 10 000	1 465	—.0042	
T 7 000	1 025	—.0026	
T 50 000	7 330	+.0050	
T 100 000	14 650	+.0120	
T 124 500	18 230	+.0167	6 6 6 6 6 6
T 60 000	8 790	+.0130	
T 7 000	1 025	+.0094	
C 10 000	1 465	+.0072	
C 50 000	7 330	—.0002	
C 100 000	14 650	—.0089	
C 125 000	17 320	—.0140	6 6 6 6 6 6
C 57 000	8 355	—.0108	
C 10 000	1 465	—.0078	
T 7 000	1 025	—.0058	
T 50 000	7 330	+.0038	
T 100 000	14 650	+.0142	
T 125 000	18 320	+.0195	
T 152 500	22 350	+.0242	6 6 6 6 6 6
T 75 000	10 990	+.0194	
T 7 000	1 025	+.0141	
C 10 000	1 465	+ 0115	
C 50 000	7 330	+.0024	
C 100 000	14 650	—.0112	
C 125 000	18 320	—.0147	
C 150 000	21 980	—.0192	6 6 6 6 6 6
C 70 000	10 260	—.0155	
C 10 000	1 465	—.0109	
0 000	0 000	—.0080	
T 7 000	1 025	—.0087	
T 50 000	7 330	+.0035	
T 100 000	14 650	+.0075	
T 150 000	21 980	+.0250	
T 176 000	25 785	+.0307	6 6 6 6 6 6
T 108 000	15 830	+.0255	
T 7 000	1 025	+.0179	
C 10 000	1 465	+.0148	
C 50 000	7 330	+.0029	
C 100 000	14 650	—.0125	
C 150 000	21 980	—.0202	
C 175 000	25 640	—.0246	6 6 6 6 6 6
C 91 000	13 340	—.0210	
T 10 000	1 465	—.0143	
T 25 000	3 665	—.0065	
T 50 000	7 330	+.0035	
T 100 000	14 650	+.0202	
T 150 000	21 980	+.0283	
T 175 000	25 640	+.0235	
T 200 500	29 370	+.0374	6 6 7 7 7 6
T 100 000	14 650	+.0309	
T 7 000	1 025	+.0213	6 6 6 6 6 6
C 10 000	1 465	+.0178	
C 50 000	7 330	+.0032	
C 100 000	14 650	—.0148	
C 150 000	21 980	—.0237	
C 175 000	25 640	—.0262	
C 200 000	29 300	- .0303	7 6 7 7 7 7
C 101 000	14 800	—.0256	
C 10 000	1 465	—.0173	6 6 6 6 6 6
T 7 000	1 025	—.0132	
T 50 000	7 330	—.0048	
T 100 000	14 650	—.0245	
T 150 000	21 980	—.0319	
T 200 000	29 300	--.0395	
T 224 000	32 820	—.0450	6 7 8 8 8 8
T 110 000	16 120	—.0385	
T 7 000	1 025	+.0248	
C 10 000	1 465	+.0205	
C 50 000	7 330	+.0000	
C 100 000	14 650	—.0174	
C 150 000	21 980	—.0253	
C 200 000	29 300	—.0322	
C 225 000	32 960	—.0372	7 6 7 7 7 7
C 120 000	17 580	—.0321	
C 10 000	1 465	—.0206	7 6 7 6 6 6
T 7 000	1 025	—.0147	
T 50 000	7 330	+.0152	
T 100 000	14 650	+.0278	
T 150 000	21 980	+.0380	
T 200 000	29 300	+ 0432	
T 225 000	32 960	+.0488	
T 251 000	36 770	+.0552	6 8 9 9 8 8
T 125 000	18 320	+.0458	
T 7 000	1 025	+.0302	6 7 8 8 7 7
C 10 000	1 465	+.0248	
C 50 000	7 330	—.0085	
C 100 000	14 650	—.0198	

TABLE 6. (*Continued.*)

Sample of Data of Test of Riveted Joints in Alternate Tension and Compression.

T denotes load in tension; C, load in compression. Shear per square inch of rivet is based on the shearing area computed from the nominal diameter of rivet—⅞ inch.

Specimen TB21F. Test No. 94.

Load pounds	Shear per Square Inch of Rivet. pounds	Elongation in 20 Inches	Drill Number of Largest Rod through Rivet. Holes 0.204 in. in Diameter
C 150 000*	21 980	—.0283	
C 200 000	29 300	—.0352	
C 250 000	36 630	—.0393	
C 250 000	36 630	—.0455	8 7 8 8 8 8
C 121 000	17 730	—.0386	
C 10 000	1 465	—.0243	7 7 7 7 7 7
T 0 000	0 000	—.0152	
T 50 000	7 330	+.0208	
T 100 000	14 650	+.0330	
T 150 000	21 980	+.0415	
T 200 000	29 300	+.0489	
T 250 000	36 630	+.0575	
T 275 000	40 300	+.0666	7 9 11 9 11 9
T 140 000	20 500	+.0550	
T 7 000	1 025	+.0392	6 8 8 8 7 7
C 10 000	1 465	+.0208	
C 50 000	7 330	—.0112	
C 100 000	14 650	—.0235	
C 150 000	21 980	—.0320	
C 200 000	29 300	—.0398	
C 250 000	36 630	—.0588	
C 275 000	40 300	—.0572	9 8 11 9 11 8
C 137 000	20 070	—.0492	
C 10 000	1 465	—.0308	8 8 8 8 8 8
T 7 000	1 025	—.0175	
T 50 000	7 330	+.0235	
T 100 000	14 650	+.0362	
T 150 000	21 980	+.0458	
T 200 000	29 300	+.0548	
T 250 000	36 630	+.0642	
T 275 000	40 300	+.0720	
T 300 000	43 960	+.0852	8 12 13 13 13 12
T 150 000	21 980	+.0722	
T 7 000	1 025	+.0502	7 9 11 11 11 9
C 10 000	1 465	+.0168	
C 50 000	7 330	—.0085	
C 100 000	14 650	—.0225	
C 150 000	21 980	—.0338	
C 200 000	29 300	—.0437	
C 250 000	36 630	—.0542	
C 275 000	40 300	—.0605	
C 300 000	43 960	—.0747	12 11 14 13 14 11
C 150 000	21 980	—.0667	
C 10 000	1 465	—.0441	11 9 11 9 11 8
T 392 800	57 550		

Failed by shearing 6 upper rivets on both sides.

*Slipped about .0100.

In four tests an effort was made to study the behavior of the test pieces under several reversals of a load which gave a shearing stress of about 10 000 lb. per sq. in. of rivet area. In Fig. 16, page 38, in the test of each riveted joint the diagram marked (1) shows the deformation of the specimen under the first cycle of load (i.e., during the application of tension, the release of tension, the application of compression, and the release of compression); diagram marked (10) shows the deformation during the tenth cycle of load; (11) shows the deformation during a cycle in which the rivet shear was increased to 15 000 lb. per sq. in.; (12) shows the next cycle which was for a load of 10 000 lb. per sq. in. rivet shear, etc.

12. *Tables and Diagrams of Results.*—Table 7 gives the shearing stress in the rivets (stated in lb. per sq. in. of the shearing area of the rivet) at which the first noticeable slip of the riveted

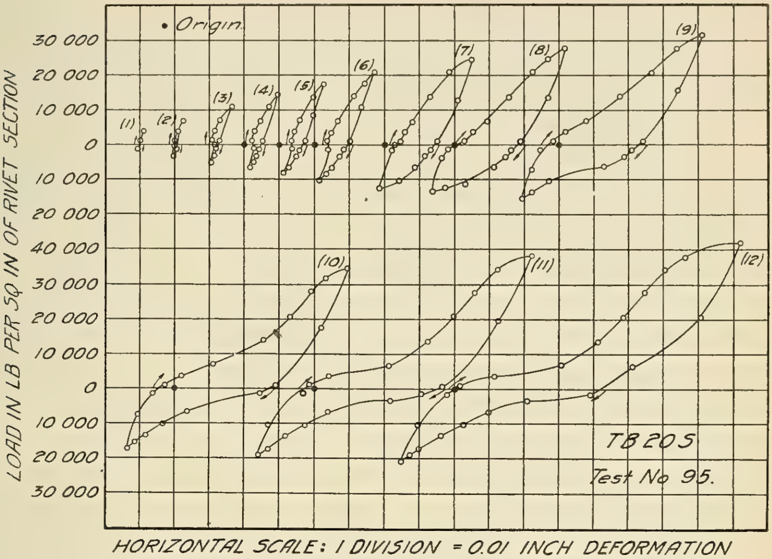


FIG. 14. DIAGRAM OF TENSION AND COMPRESSION TEST NO. 95.

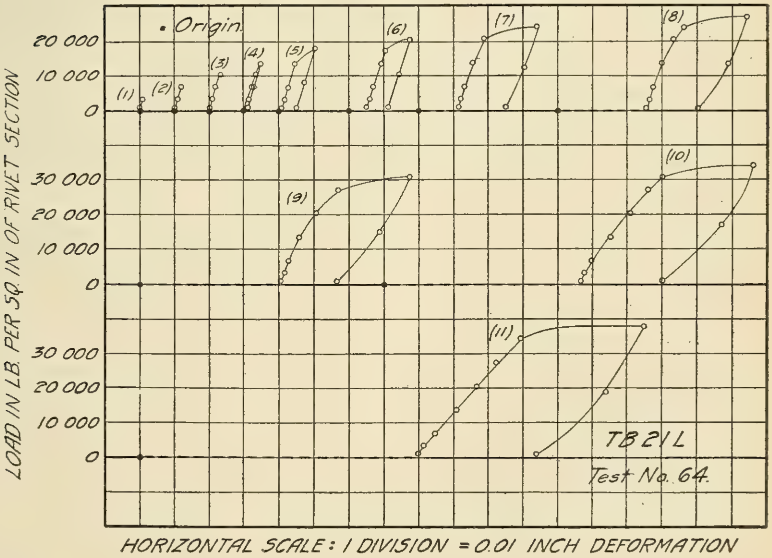


FIG. 15. DIAGRAM OF TENSION TEST NO. 64.

TABLE 7.

FIRST NOTICEABLE SLIP OF RIVETED JOINTS.

Loads are given in terms of the stress in pounds per square inch on the nominal shearing area of the rivets.

Test piece	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Nickel-steel Riveted Joints.																		
Shop riveted	8 900 10 500 11 000	10 500 6 300 11 000	8 200 5 600 15 000	7 500 6 900 7 600	6 100 8 000	6 000 6 000 5 900	10 000 9 000 8 800	9 500 10 000 10 500	11 600 12 200 10 500	12 500 9 000 11 800	11 500 12 500 13 000	13 000 14 000 12 500	9 500 12 000 8 600	11 500 10 000 10 500	15 000 11 000 14 100	11 000 17 500 13 000	14 000 14 500 12 500	15 500 18 000 10 500
Field riveted	10 500 17 000	17 500 13 000	15 000 10 500	5 200 10 000	5 500 5 800	5 600 5 600	8 000 7 500	6 600 9 700	8 800 7 500	8 600 7 500	9 100 9 000	8 500 7 500	11 100 8 400	12 500 8 500	11 400 11 000	9 500 9 500	13 000 11 000	15 000 14 000
Av. shop riveted	10 130	9 270	9 600	7 330	7 050	5 970	9 270	10 000	11 430	11 100	12 330	13 000	10 030	10 670	13 370	13 830	13 800	14 670
Av. field riveted	10 750	15 250	12 750	7 605	5 650	5 600	7 750	8 150	8 150	8 050	9 050	8 000	9 750	10 500	11 200	9 500	12 000	14 500
Av. shop and field riveted	10 380	11 660	10 860	7 440	6 350	5 820	8 660	9 260	10 120	9 880	11 020	11 100	9 920	10 600	12 500	12 080	13 080	14 600
General average 10 300																		
Chrome-nickel-steel Riveted Joints.																		
	13 000 15 000 15 000	13 000 14 000 13 500	11 000 13 500 11 000	11 500 10 000 10 000	12 000 12 000 13 000	10 500 11 500 10 000	12 000 12 000	14 500 14 000 13 500	14 000 13 000 11 500	13 500 13 500 11 500	16 500 14 000 14 000	16 500 15 000 15 000	16 500 16 500 14 000	15 000 16 500 12 500	16 000 18 000 10 000	15 000 15 000 16 000	15 000 13 500 19 000	16 500 16 500 13 500
Average	14 330	13 500	11 830	10 500	12 330	10 670	12 000	14 000	12 830	12 830	14 830	15 500	15 670	14 670	14 670	15 330	15 830	15 500
General average 13 690																		
Carbon-steel Riveted Joints. (Maintenance of Way Association Tests).																		
	27 000 17 000 18 000 20 000 19 000	13 000 14 000 14 500 16 500 13 000	8 000 13 500 10 500 12 500 12 500	16 000 15 000 11 500 11 500 12 500	14 000 12 500 7 500 7 000 11 500	6 500 7 000 7 500 5 500 5 500	6 500 6 500 7 500 7 000 7 500	7 500 8 000 7 000 7 000	12 000 13 500 12 000 11 000 9 000	6 000 8 000 7 000 6 000 7 500	6 000 6 000 9 000 10 500 9 500	8 000 10 000 11 000 13 500 11 000	9 000 8 500 9 000 10 000 8 000	6 000 6 500 7 000 7 000 7 500	8 500 5 500 6 000 6 000 5 000	6 500 6 500 4 000 8 500 6 000	5 000 4 500 5 000 6 500 6 000	5 500 6 000 7 000 5 500 6 500
Average	20 200	14 200	11 400	13 300	10 500	6 400	7 000	7 380	11 500	6 900	8 200	10 700	8 900	6 800	6 200	6 300	5 400	6 100
General average 9 310																		

joint occurred in the tension tests. In all cases in computing the area of a rivet the nominal diameter of the rivet was used. The shearing stress is taken at the load at which the total apparent movement amounted to about 0.0025 in. The determination of this point involves the use of some judgment, but as the same method was used in all cases the results are considered to be comparable with each other.

Table 8, page 32, gives the yield point of the nickel-steel and the chrome-nickel-steel riveted joints stated in terms of the shearing stress on the rivets.

In Fig. 17 and 18 (at the end of the text) permanent set is plotted for the nickel-steel riveted joints, the chrome-nickel-steel riveted joints, and the carbon-steel riveted joints. In each case the results given are the average for the test pieces of the set. A general comparison may be made by eye.

Table 9, page 34, gives the ultimate strength of the nickel-steel and of the chrome-nickel-steel riveted joints stated in lb. per sq. in. of the shearing area of the rivets. In computing rivet area the nominal diameter was used. The ultimate strength of the carbon-steel joints reported by the Maintenance of Way Association is also given.

Table 10 gives the ultimate shearing strength and Table 11, the yield point of riveted joints tested in alternate tension and compression.

Fig. 19 to 22 (at the end of the text) show graphically the total deformation produced by different intensities of stress. In the direct tension and direct compression tests, the set is also plotted, and in the other tests except tests 69, 70, 105, and 106, both the total range of deformation and the deformation under tension are given. Table 11 gives the yield point of the joints tested in alternate tension and compression.

13. *Slip in Tension Tests.*—By the use of delicate extensometers slip of the rivets in a test joint can be detected and measured under small loads. An inspection of Fig. 17 and 18 shows that the plates began to slip at loads as low as the usual working loads, the amount of slip increasing regularly until the yield point of the joint was reached. The first noticeable slip of the riveted joint given in Table 7 is taken when the total apparent movement amounted to 0.0025 inch. The slip of joint in the Maintenance of Way tests of carbon-steel riveted joints is also included in Table 7.

TABLE 8.

YIELD POINT OF RIVETED JOINTS.

Loads are given in terms of the stress in pounds per square inch on the nominal shearing area of the rivets.

Test Piece	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Nickel-steel Riveted Joints																		
Shop riveted	37 800 35 500 36 600*	36 200 35 500 34 500*	30 600 32 100 35 500*	35 000 34 100 34 900*	30 100 35 100 34 100*	31 600 37 000 33 300*	31 400 32 700 31 400*	36 200 35 500 35 700*	36 800 37 700 38 300*	29 900 29 200 27 800*	34 900 37 600 36 200	40 100 37 500 38 200*	35 000 35 000 34 300*	28 900 28 300 27 500*	32 300 31 900 33 700	34 000 35 600 35 200	28 800 27 600 27 000	31 800 32 500 30 000
Field riveted	37 000 35 500	35 800 38 000	34 300 34 000	37 000 34 500	34 000 36 800	35 700 35 100	34 000 32 500	36 800 37 000	36 200 37 200	30 200 30 000	35 300 34 200*	36 800 37 000	40 000 36 100	29 200 31 300	34 100 32 700*	34 500 35 000	27 000 28 000	31 700 29 800
Av. shop riveted	36 630	35 400	32 730	34 670	33 100	33 970	31 830	35 800	37 600	28 970	36 230	38 600	34 770	28 230	32 630	34 930	27 800	31 430
Av. field riveted	36 250	36 900	34 150	35 750	35 400	35 400	33 250	36 900	36 700	30 100	34 750	36 900	38 050	30 250	33 400	34 750	27 500	30 750
Average shop and field riveted	36 480	36 000	33 300	35 100	34 020	34 540	32 400	36 240	37 240	29 420	35 640	37 920	36 080	29 040	32 940	34 860	27 680	31 160
Yield point of rivet in bending	38 600	32 400	32 500	35 000	32 600	29 000	31 000	32 700	37 400	23 500	35 600	32 100	31 500	22 000	28 100			
Chrome-nickel-steel Riveted Joints.																		
	34 500 37 200 38 000	36 800 34 000 37 500	36 500 34 500 35 500	35 000 36 000 39 200	32 000 36 000 36 200	36 000 34 700 37 300	31 300 29 800 32 000	34 000 33 800 31 300	37 000 35 700 34 600	24 500 24 000 24 400	29 500 30 200 28 700	34 500 30 900 31 100	32 300 30 600 30 600	25 500 25 000 25 000	28 100 30 500 28 000	31 000 32 200 30 000	23 400 24 100 25 000	27 800 27 500 27 000
Average	36 570	36 100	35 500	36 730	34 730	36 000	31 030	33 030	35 770	24 300	29 470	32 170	31 170	25 170	28 870	31 070	24 170	27 430
Yield point of rivet in bending	36 300	36 000	33 600	38 000	35 000	36 700	30 900	32 000	35 200	24 400	29 000	32 800	30 600	25 500	29 100	31 500	24 200	27 100

* Joint with hole drilled through rivet.

TABLE 8.—(*Continued.*)

YIELD POINT OF RIVETED JOINTS.

Loads are given in terms of the stress in pounds per square inch on the nominal shearing area of the rivets.

Test Piece	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Carbon-nickel-steel Riveted Joints—(Maintenance of Way Association Tests).																		
	28 000	24 900	26 100	28 800	29 600	24 700	20 100	26 600	26 100	19 400	25 000	29 500	28 500	18 600	20 700	21 200	15 800	17 600
	31 400	27 100	26 400	27 000	27 600	23 000	19 300	25 000	25 800	19 500	23 300	27 500	28 000	20 600	19 800	17 700	16 000	16 800
	29 900	25 500	27 100	28 000	25 100	23 000	19 400	27 400	23 800	19 300	25 100	26 000	27 800	18 900	19 600	21 500	15 400	17 600
	31 000	27 000	25 200	27 700	26 800	21 600	21 900	26 200	27 800	19 400	19 800	27 800	28 900	18 700	21 700	22 300	16 000	16 600
	32 800	26 300	24 100	26 000	29 300	24 100	22 800	28 000	27 900	19 400	22 300	26 000	27 900	18 800	20 000	22 000	16 000	17 000
Average	30 620	26 160	25 780	27 500	27 680	23 280	20 700	26 640	26 280	19 400	23 100	27 360	28 220	19 120	20 360	20 940	15 840	17 120
Excess of nickel steel over carbon steel, per cent	19 2	37.6	29.6	27.6	23.0	48.4	56.6	36.4	41.8	51.8	54.4	38.7	27.9	52.0	61.9	66.5	75.0	82.0
Excess of chrome nickel steel over carbon steel, per cent	19.4	37.7	37.6	33.5	25.5	54.7	50.0	24.0	36.1	25.4	27.6	17.6	10.3	31.6	41.8	48.3	53.0	60.2

TABLE 9.

ULTIMATE SHEARING STRENGTH OF RIVETED JOINTS.

Loads are given in terms of the stress in pounds per square inch on the nominal shearing area of the rivets.

Test piece	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Nickel-steel Riveted Joints.																		
Shop riveted.	63 900 58 900 60 600*	58 600 58 080 58 300*	55 000 55 600 57 500*	57 700 56 700 55 800*	46 950 56 600 55 800*	56 500 56 700 54 800*	55 900 56 100 55 500*	57 700 58 900 58 200*	57 700 57 600 58 400*	55 100 54 300 53 300*	55 200 58 000 57 600	59 700 56 400 57 500*	55 700 56 600 57 800*	51 400 53 000 52 300*	53 700 54 200 55 000	53 700 55 300 56 900	55 000 56 600 54 500	56 000 55 400 55 300
Field riveted........	60 000 57 300	56 900 58 500	56 300 56 200	59 400 59 000	58 300 58 000	58 400 58 400	57 200 57 600	59 300 59 300	58 100 57 600	55 000 56 100	57 700 57 300*	59 700 57 700	57 500 57 400	52 400 53 100	57 200 56 600*	56 700 56 700	56 200 53 400	55 300 54 600
Av. shop riveted....	61 130	58 300	56 030	56 730°	53 100	56 000	55 830	58 270	57 900	54 230	56 930	57 870	56 700	52 230	54 300	55 300	55 400	55 570
Av. field riveted....	58 650	57 700	56 250	59 200	58 150	58 400	57 400	59 300	57 850	55 550	57 500	58 700	57 450	52 750	56 900	56 700	54 400	54 950
Av. shop and field riveted	60 140	58 080	56 120	57 720	55 120	56 960	56 460	58 460	57 880	54 760	57 160	58 200	57 000	52 440	55 340	55 860	55 140	55 320
Max. tensile stress in plate (lb. per sq. in.)	18 150	33 300	48 950	16 850	33 100	49 700	49 100	49 600	49 700	47 800	49 400	50 800	48 400	45 300	47 900	47 600	47 400	46 800
Chrome-nickel-steel Riveted Joints.																		
	53 350 56 400 56 900	57 100 54 250 57 650	55 700 53 850 55 750	54 550 57 300 58 100	52 700 55 650 56 550	53 940 54 500 56 300	51 300 51 450 53 100	55 000 53 250 51 600	53 950 55 200 53 620	48 900 48 150 47 530	51 550 53 420 50 600	54 800 51 520 50 720	52 450 53 000 52 050	48 400 48 300 49 000	51 350 51 550 50 450	51 950 52 800 51 280	51 150 49 620 50 650	51 320 50 900 50 920
Average............	55 550	56 330	55 100	56 650	54 970	54 910	51 950	53 280	54 260	48 190	51 860	52 350	52 500	48 570	51 120	52 010	50 470	51 050
Max. tensile stress in plate (lb. per sq. in.)..	16 170	32 750	49 500°	16 510	32 200	48 000°	45 250°	46 840°	45 950°	41 650°	45 550°	46 650°	44 350	41 000	43 150	44 180	42 800	42 950

* Joints with hole drilled through rivets. ° Plate after rupture showed "stress lines" indicating that the yield point of the plate material had been passed.

TABLE 9.—(*Continued.*)

ULTIMATE SHEARING STRENGTH OF RIVET JOINTS.

Loads are given in terms of the stress in pounds per square inch on the nominal shearing area of the rivets.

Test piece	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Carbon-steel Riveted Joints (Maintenance of Way Association Tests).																		
	53 200 36 600 54 900 54 500 55 700	47 600 48 400 48 200 48 100 49 100	45 700 44 900 45 500 47 120 45 700	53 500 50 700 52 100 52 400 51 600	50 100 50 400 50 600 50 900 52 400	48 500 45 300 47 400 47 900 45 500	50 000 47 800 45 700 50 900 49 200	48 800 48 900 49 500 50 400 49 900	48 800 48 900 48 800 50 400 56 800	46 300 50 800 45 000 52 100 47 500	48 800 44 000 50 100 51 400 50 800	53 900 48 400 51 400 48 200 47 600	48 800 54 700 49 200 48 500 51 500	46 900 46 600 44 000 47 700 45 100	49 200 48 000 46 800 48 100 46 800	48 400 45 000 45 900 50 000 48 500	45 400 44 600 44 300 45 500 44 900	45 500 46 300 47 300 46 300 46 200
Average.............	50 980	48 280	45 780	52 060	50 880	46 920	48 720	49 500	50 740	48 340	49 020	49 900	50 540	46 060	47 780	47 760	44 940	46 320
Max. tensile stress in plate (lb. per sq. in.)...............	15 800	27 900	40 100	15 190	29 800	41 300	43 300	42 900	48 400	44 300	43 700	45 900	45 800	39 900	41 200	41 800	37 100	39 600
Excess of nickel-steel over carbon steel in shearing stress (per cent)..	17.2	20.4	22.7	10.9	8.4	21.4	13.9	18.2	13.2	13.3	16.5	16.7	12.9	14.0	15.9	17.2	22.6	19.4
General average....	16.4																	
Excess of chrome-nickel-steel over carbon steel (per cent)..............	9.1	16.6	20.5	8.9	8.2	17.1	6.6	7.7	7.0	—1.5	5.6	5.1	4.0	5.3	7.0	9.1	12.5	10.4
General average....	8.85																	

TABLE 10.

Alternate Tension and Compression Tests.
Ultimate Shearing Strength of Riveted Joints.

Loads are given in terms of the stress in pounds per square inch on the nominal shearing area of the rivets.

Nickel-steel Riveted Joints			Chrome-nickel-steel Riveted Joints		
Joint	Load at Failure lb. per sq in.	Remarks	Joint	Load at Failure lb. per sq. in.	Remarks
Riveted Joints Subjected to Tension only.					
TB20S	56 700		TB20L	52 400	
TB21S	58 100		TB20L	49 800	
TB22F	58 800		TB21L	49 800	
Av.	57 870		Av.	50 670	
Riveted Joints Subjected to Compression only.					
TB20F		End of plates butted.	TB19L		Joints buckled. Plates butted.
TB22S	55 600	Rivets sheared.	TB20L		
TB22F		Joint buckled.	TB22L		
Riveted Joints Subjected to Tension followed by Half as Great Compression.					
TB20S	57 400		TB19L	50 200	
TB22S	55 200		TB19L	49 700	
Av	56 300			49 950	
Riveted Joints Subjected to Tension followed by Equal Compression.					
TB19S	56 200		TB19L	49 500	
TB20S	56 600		TB20L*	49 300	
TB21S	55 820		TB21L*	51 700	
			TB21L°	50 800	
			TB21L°	51 600	
Av. shop riveted	56 200		TB22L	51 600	
			TB22L	52 000	
TB19F*	58 260		TB22L	51 700	
TB19F°	57 500				
TB20F	57 700		Av.	51 020	
TB21F*	57 550				
TB21F°	60 250				
Av. field riveted	58 230				
Av. field and shop riveted	57 480				

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* Riveted joints with holes drilled through rivets.

° Riveted joints subjected to cycles of reversed load causing a shearing stress in the rivets of 10 000 lb. per sq. in.

TABLE 11.

Alternate Tension and Compression Tests.
Yield Point of Riveted Joints.

Loads are given in terms of the stress in pounds per square inch on the nominal shearing area of the rivets.

Nickel-steel Riveted Joints				Chrome-nickel-steel Riveted Joints			
Joint	Load at Yield Point lb. per sq. in.	Range of Deformation at Yield Point		Joint	Load at Yield Point lb. per sq. in	Range of Deformation at Yield Point	
		Under Load inches	Set inches			Under Load inches	Set inches
Riveted Joints Subjected to Tension only.							
TB20S	34 000	0.050	0.030	TB20L	29 500*	0.067	0.047
TB21S	34 600	0.045	0.028	TB20L	32 000	0 027	0.020
TB22F	36 100	0.041	0.028	TB21L	23 000*	0.040	0.027
Av.	34 900	0.045	0.029	Av.	28 170	0.045	0.032
Riveted Joints Subjected to Compression only.							
TB20F	37 000	0.035	0.020	TB19L	18 000*		
TB22S	33 700	0.045	0.030	TB20L	30 500	0.040	0.030
TB22F	36 200	0.035	0 020	TB22L	31 200	0.035	0.025
Av.	35 630	0.038	0.023	Av.	30 850§	0.037	0.027
Riveted Joints Subjected to Tension followed by Half as Great Compression.							
TB20S	39 000	0.079		TB19L	20 700*	0.015	
TB22S	38 900	0.095		TB19L	24 300*	0.017	
Av.	38 950	0.087		Av.	22 500	0.016	
Riveted Joints Subjected to Tension followed by Equal Compression.							
TB19S	33 800	0.089		TB19L	17 200*	0.015	
TB19F†	36 600	0.085		TB20L†	15 700*	0.017	
TB20F	36 400	0.092		TB21L†	15 300*	0.013	
TB20S	34 800	0.095		TB22L	19 500*	0.027	
TB21S	31 800	0.088		TB22L	16 000*	0.015	
TB21F†	36 500	0.100		TB22L	15 000*	0.015	
Av.	34 970	0.091		Av.	16 450	0.017	
Riveted Joints Subjected to Cycles of Reversed Load Causing a Shearing Stress in the Rivets of 10 000 lb. per sq. in.							
TB19F	30 300	0.045‡		TB21L	24 100	0.050‡	
TB21F	32 700	0.052‡		TB21L	25 900	0.055‡	
Av.	31 500	0.049		Av.	25 000	0.052	

* Yield point not well defined.

† Riveted joints with holes drilled through rivets.

‡ Range in deformation in tension.

§ TB19L omitted in taking average.

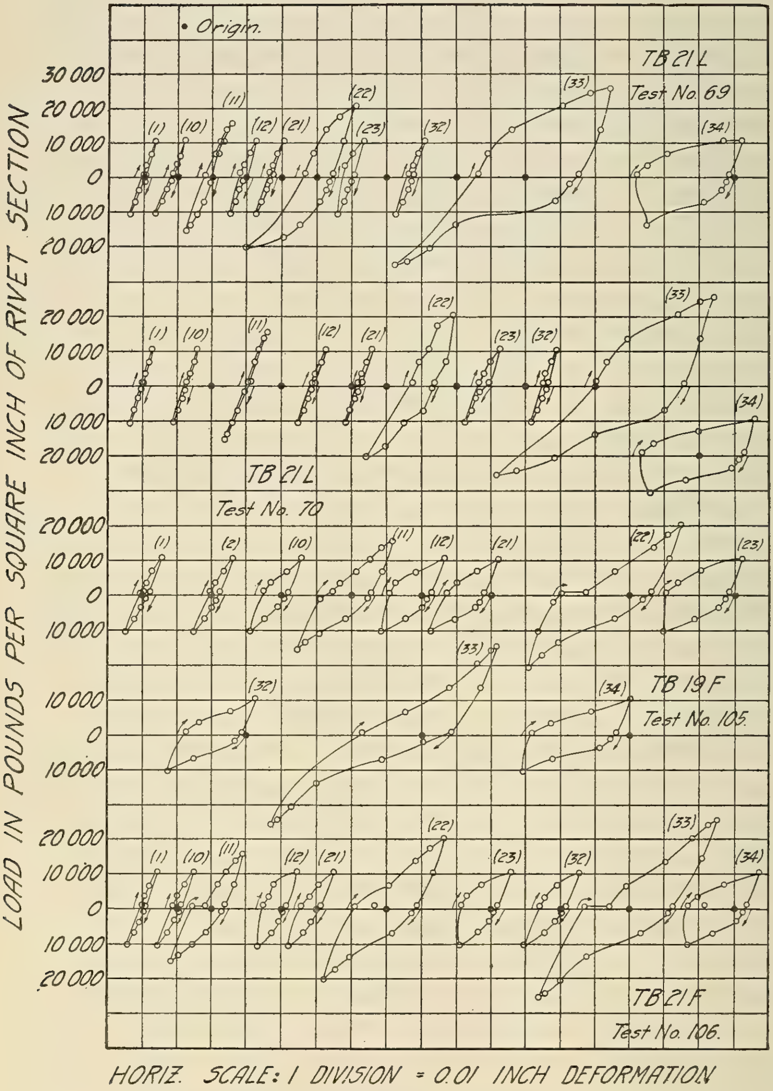

FIG. 16. DIAGRAM OF TENSION AND COMPRESSION TESTS UNDER ALTERNATIONS OF LOW STRESSES.

In general, the nickel-steel riveted joints showed first noticeable slip under a slightly higher load than that producing first noticeable slip in the carbon-steel joints of the Maintenance of Way Association. It may be doubted whether a comparison of the general averages would be significant. If the first slip of the joint is caused by the overcoming of the friction of the rivet heads and plates, no reason is apparent for expecting a higher load at first slip in nickel-steel riveted joints than in carbon-steel riveted joints, and the higher resistance of the nickel-steel riveted joints as compared with the carbon-steel riveted joints may be due to differences in fabrication.

In the tests of chrome-nickel-steel riveted joints, both plates and rivets were made up of steel softer and weaker than that used in the nickel-steel riveted joints, but the first noticeable slip took place at a load considerably higher than the load causing first slip in either the nickel-steel joints or the carbon-steel joints, indicating that the strength of material has very little effect on the stress at first slip of joint.

14. *Yield Point in Tension Tests.*—The term "yield point of riveted joints" will be used to designate the point at which a marked increase of yield in the riveted joint occurs and at which also a marked set of the riveted joint is found. As the loads are increased beyond the load causing a first noticeable slip, the permanent set increases regularly for several increments of load, as if the rivets were gradually seating themselves against the sides of the rivet holes; then quite suddenly the set increases markedly and the slope of the set curve becomes noticeably less. The method of determining the yield point in the tension tests is shown in Fig. 12. Some judgment must be exercised in determining this point, but it is quite definite except for the joints with long rivets. The increased deformation seems to be due partly to bending of the rivet and partly to shearing detrusion. Before the yield point is reached, a considerable movement of the riveted joint as a whole has taken place, and, of course, beyond the yield point the deformation increases rapidly. As measured by the displacement of the paper strips, the amount of slip up to the yield point in the riveted joints with short rivets and without filler plates was about 0.025 in., and after rupture the slip of the unbroken end was about 0.20 in. After the yield

point of the joint had been passed, the movement was due in greater part to the shearing detrusion of the rivet. In the joints with long rivets, a greater movement occurred, as much as 0.05 in. before the yield point was reached, and after rupture as much as 0.40 in. in the unbroken end of several of the riveted joints.

15. *Ultimate Strength in Tension Tests.*—All the riveted joints tested, both nickel-steel and chrome-nickel-steel, finally failed by shearing of rivets. The ultimate shearing stress in the rivets is given in Table 9. Whether a riveted joint will fail by shear of rivets or otherwise depends upon the design of the joint and the relative strength of the rivet and plate material. A fact not always recognized is that the stress at which a rivet will break under shear depends not only upon the quality of the rivet material but also on the relative hardness of the rivet and of the plate on which the rivet bears. The rivet material used in the nickel-steel riveted joints was about 16 per cent stronger in tension than that used in the chrome-nickel-steel riveted joints; the plate material of the nickel-steel riveted joints was considerably stronger and harder than the rivet material, while in the chrome-nickel-steel riveted joints the plate material was not much stronger than the rivet material; the result was the shearing strength of the nickel-steel riveted joints was only 7 per cent greater than that of the chrome-nickel-steel riveted joints, about half of the gain which might be expected from a comparison of the tests of rivet material.

Comparing the ultimate strength of the Maintenance of Way Association tests of carbon-steel riveted joints, the apparent gain in ultimate strength is only about 16 per cent for the nickel steel and about 9 per cent for the chrome nickel steel. However, the carbon-steel riveted joints were designed so as to have nearly the same strength in shear of rivets and in tension in plates; this is shown by the fact that some failed by shear of rivets and some by tension in plates. The tensile stresses in the plates forming the riveted joints, developed at the ultimate load, are given in Table 9. In the case of the nickel-steel riveted joints it will be noted by reference to the strength of the specimens cut from the plates (see Table 2) that even in the riveted joints in which three or six rivets were sheared the tensile stress in the plate at rupture of the riveted joint was in no case as great as the yield point of the material of the plates. The nickel-steel and the chrome-nickel-steel riveted joints were made with the same dimensions as the Maintenance of Way Association riveted joints and as they all failed by shear of rivets and as no scaling or other indication of exceeding the yield point of the plates was observed in the nickel-steel riveted joints, and no chrome-nickel-steel riveted joints failed in the plates, (though many of the plates in the chrome-nickel-steel riveted joints were stressed beyond the yield points as was shown by "scaling" and by the appearance of characteristic "stress lines",) it is evident that the efficiency of joint was less than in the carbon-steel joints, and that a larger gain could have been shown for the nickel-steel and chrome-nickel-steel riveted joints had they been proportioned so as to have as high joint efficiencies as had the Maintenance of Way Association carbon-steel joints. The tests, therefore, may not be used to compare the full strength of riveted joints of the three classes of materials.

In connection with this topic the results of the tests made by Preuss at Darmstadt are of interest (see foot note on page 5). In the test joints of that series nearly all the rivets were of nickel steel. The plate material was not specified, and Dr. Preuss writes that its nature is not known; it probably was ordinary structural steel. At any rate, judging from the rivet material, it seems probable that the rivets of the joints were of stronger and harder material than were the plates. Comparing the butt joints in Preuss' tests with those most nearly similar in the University of Illinois tests, the ultimate shearing stress in the rivets of Preuss' test joints was about 19 per cent greater than the ultimate shearing stress in the rivets of the corresponding Illinois test joints. In view of the fact that in the University of Illinois tests the plate material was stronger and harder than the rivet material, while in Preuss' tests the reverse is true, the difference in shearing strength does not seem excessive. Making similar comparisons for lap joints in the two series of tests, Preuss' results for ultimate shearing stress in rivets are about 39 per cent higher than those found at Illinois. This great difference in ultimate strength may be due in part to the fact that the riveted ends of the lap joints in Preuss' tests were bent during fabrication to make the center of the rivet come in the direct line of the pull on the joint.

16. *Slip in Alternate Tension and Compression Tests.*—The slip of the riveted joints in the alternate tension and compression tests is shown by the diagrams in Fig. 13 to 16. The most striking feature in the tests under alternate tension and compression is the very large slip which may take place under comparatively low loads. Especially is there danger of a large amount of slip if at any time a riveted joint has been subjected to a single load considerably beyond the ordinary working load. In Fig. 16, if cycle (1) is compared with cycle (12) there is seen a marked increase in the amount of slip under loads below ordinary working loads; this slip occurred in the joint after a single application of an unusually high load.

17. *Yield Point in Alternate Tension and Compression Tests.*—In the tension tests the yield point of the riveted joints was in general determined from the set curve (see Fig. 12); but in tests in alternate tension and compression there is very little set at the end of a cycle of stress and the amount of this is not significant. In these tests the yield point has been located by J. B. Johnson's method which consists in finding a point on the stress deformation curve where the rate of change of deformation is 50 per cent greater than during the early part of the test. The average yield point obtained in this way does not differ much from that obtained by taking the first marked change in direction of the stress-deformation curve. Where bending of rivet was directly examined, the first noticeable set of rivet took place at a stress not widely differing from the yield point as determined by the above method. From the results of the tests it would seem that the riveted joints tested under alternate tension and compression showed yield points about as high as those tested under stress in one direction only. Attention is called to the lower yield points found in Tests 69, 70, 105, and 106, in which the joints had been subjected to repeated applications of the load.

18. *Ultimate Strength in Alternate Tension and Compression Tests.*—Of the series of riveted joints for alternate tension and compression loads, six were tested in direct tension and six in direct compression. This was done to furnish a basis of comparison for the alternate tension and compression tests. Every joint of the series failed by shear of rivets, except that in nearly all of the direct compression tests the main plates finally came in di-

rect contact and the joints buckled noticeably, thus preventing the completion of the shearing action. In the one compression test in which the rivets were sheared to failure, the joint buckled noticeably and the failure was on the concave side of the joint. In the tension failures, in some cases rivets sheared on both sides of the main plates and in other cases on one side only. The joints failed suddenly with a loud report, the load falling off slightly just before failure. In no case was there any indication that either the main plates or the cover plates had reached their elastic limit when the ultimate load was applied.

The comparatively few alternations of load to which the nickel-steel and the chrome-nickel-steel riveted joints were subjected apparently had very little effect on the ultimate strength, as may be seen by comparing the ultimate strengths with those of the joints tested in tension. It is entirely probable, however, that a large number of reversals of load would cause failure under lower loads. Reversed load tests involving a large number of loadings on full-sized riveted joints have never been made, so far as is known. Such tests would be very expensive and would require a long time. In the absence of such tests it may be assumed that riveted joints under repeated reversals of load would be in danger of failure at loads very much lower than under steady tension loads.

19. *Bending of Rivets.*—It has long been recognized that in riveted joints the rivets are subjected to bending stresses, and attempts have been made to calculate these stresses. A mathematical analysis of the bending of a rivet is subject to many uncertainties: the ends of the rivets are partially restrained; the compression and detrusion of the rivet and plate modify the bending action and render uncertain the position of the point of application of the resulting pressure; and in various ways the conditions of beam action are indeterminate. The investigation of bending of rivets made in these tests is novel, so far as known. It shows to what extent bending takes place in such joints. The first marked bending of the rivets was found to be closely coincident with the yield point of the joint. It is seen also that the longer the rivet the greater the relative importance of the resistance to bending. It will be noted that in those joints having long rivets (TB14 to TB18) the nickel-steel riveted joints have their yield point at a stress considerably higher than do the carbon-

steel riveted joints, and that the yield point of the chrome-nickel-steel riveted joints is between the two.

In the alternate tension and compression tests, the load at which actual appreciable bending of the rivets first takes place (also generally coincident with the yield point of the joint) seems to be slightly lowered by a few applications of alternate tension and compression.

20. *Action of Riveted Joints under Steady, Repeated, and Alternated Loads.*—The tests indicate in a general way the behavior which may be expected in a riveted joint of a structure under various kinds of loading. Under a steady load in one direction, a slight slip may be expected under ordinary working loads, and the deformation of the structure will be greater than if it contained no riveted joints. Under ordinary loads the deformation due to slip of rivets will not be at all serious. If the joint were subjected to repeated applications of working load in the same direction, probably the deformation due to slip would increase but little after the first few applications of the load; in this case there would be a small permanent deformation of the structure, which would not be large enough to cause trouble, and which would increase but very little under successive loads. If the joint were subjected to ordinary working loads acting first in one direction and then in the other, the slip of rivets would doubtless be much greater than under a steady load or a repeated one-direction load of maximum amount equal to the maximum value of the alternated load. Under such stresses as are sometimes used in practice, this slip might increase under repetition of load, the joint working loose until the frictional hold of the rivet heads was greatly lessened and perhaps reduced to zero. Moreover, a single application of an overload, from accidental or other causes, might greatly increase this slip under succeeding working loads. The resulting deformation in the structure might become so great as to seriously impair its usefulness.

If a riveted joint in any structure be loaded beyond the yield point, the resulting deformation in the structure may be large enough to seriously injure it. If a riveted joint is stressed beyond the yield point under a long continued load, it might eventually fail, though data on this point are lacking. If a riveted joint is repeatedly stressed beyond the yield point by loads always acting in the same direction, the probability is that it would eventually fail. If a riveted joint is repeatedly stressed beyond the yield point by loads acting first in one direction and then in the other, the probability of failure would be great.

21. *The Basis for Design of Riveted Joints.*—It has been held that riveted joints should be designed on the basis that there will be no slip of plates at working loads and that the friction between the plates will be sufficient to sustain ordinary working loads and to prevent bearing stresses on the rivets. The experimental evidence of these tests, and of other tests already referred to shows that it would be futile to attempt to design riveted joints which shall have zero slip, whether the rivets be of carbon steel or of nickel steel. Slip must be expected below the ordinary working stresses, and if for any reason the assumed stresses are exceeded the slip of the joint will increase rapidly. It seems evident that with ordinary workmanship, the frictional hold of the plates is not an available asset of strength.

If the ultimate shearing strength of the rivets and the ultimate tensile strength of the plate are used as the basis of design, it will be important to know the shearing strength of the rivet material when used with the plate material of the riveted joints. The results of tests of shearing strength of rivet material which have been made in hardened steel dies are not directly applicable. If the shearing strength of rivet steel tested in connection with plates of the same degree of hardness be considered to be 0.80 of the tensile strength of the rivet material, it may be expected that with harder plates the ratio of shearing strength of rivet to tensile strength of rivet will be less, reaching three-quarters or even two-thirds; the ratio of shearing strength of rivet to tensile strength of plate will, of course, be still smaller. On the other hand, if the plate is softer than the rivet, the shearing strength of the rivet will be greater than otherwise. In designing riveted joints on the basis of ultimate strength, then, the shearing strength of the rivet material when used with the plate material of the riveted joint should be known. With the stronger plate material, such as nickel steel, the relatively low strength of rivet material is something of a handicap, though the higher the strength of the rivets the less this is.

Another basis which might be used is the yield point of the joint, the point at which a marked increase of yield in the riveted joint occurs. This point in the tests described seems to be coincident with the first marked increase of set of the riveted joint and generally also with the first marked bending of the rivets. In designing, this yield point of the riveted joint could be coordinated with the yield point of the plate material. The average yield point of the nickel-steel riveted joints was about 35 000 lb. per sq. in. of rivet section. The yield point of the nickel-steel plate material was 51 700 lb. per sq. in. The ratio of the yield point of riveted joint to ultimate shearing strength of riveted joint in both series of tests was about the same as the ratio of the yield point of the plate material in tension to the ultimate tensile strength of the plate material. A design of joint might be made giving equal strength for yield point of joint and yield point of net section of plate in tension. With this basis of design, it would be important to know more definitely the cause of the increase of the movement of the joint at the yield point. If it is mainly a distortion and shearing detrusion of the rivet, the hardness of the rivet material will be a governing consideration. If the bending of the rivet is of importance, the greater bending strength of the nickel-steel rivet will be of service. This feature of the action of riveted joints is worthy of further investigation.

The foregoing applies to riveted joints with the load applied in one direction only. For alternated loads, the first slip is of more importance, repetitions increase the movement, and an occasional overload makes still greater increase. Although the ultimate strength and the yield point do not seem to be seriously affected by a few alternations of load, it seems wise to keep the shearing stresses in riveted joints subjected to alternated loading so low that slip of joint will be small. For such conditions the advantage in the use of nickel-steel rivets is open to question especially if it is found, as has been claimed, that it is difficult to drive nickel-steel rivets in such way as to give effective grip on the plates they hold together.

22. *Summary.*—The following review is given:

1. A total of 90 nickel-steel riveted joints and of 54 chrome-nickel-steel riveted joints were tested in tension. These riveted joints duplicated in dimensions the series of carbon-steel riveted joints reported by the American Railway Engineering and Maintenance of Way Association. Sixteen nickel-steel riveted joints and sixteen chrome-nickel steel riveted joints were tested in tension, compression and alternate tension and compression. Stretch,

slip, and set of riveted joints were observed, and the bending of rivet was determined by means of holes drilled axially through the rivets.

2. In the tests there was a noticeable slip of joint generally at loads within ordinary working shearing stress of rivet. The movement of the joint increased fairly regularly to a load averaging about 35 000 lb. per sq. in. of rivet shear for the nickel-steel riveted joints, when a marked increase of movement was found. This increase was closely coincident with a marked set of the joint and with a marked bending of the rivet. All the riveted joints failed by shear of rivets, as was to be expected, at ultimate shearing stresses which ran fairly uniform in both the nickel-steel series and the chrome-nickel-steel series for all the types of joint tested.

3. The experimental evidence indicates that the resistance of the joint to first noticeable slip of rivet depends more upon the workmanship of the riveting than upon the quality of the rivet material, though the contractile and gripping properties of the rivets have an influence.*

4. The yield point of a riveted joint, taken as the load at which a marked increase of yield occurs, seemingly indicates a definite property of the riveted joint. This phenomenon is worthy of further investigation. The first marked bending of the rivets was found to be closely coincident with the yield point of the joint. It was found that the longer the rivet the greater the relative importance of the resistance to bending. In the alternate tension and compression tests the first appreciable bending of the rivet seemed to be slightly lowered by a few applications of load.

5. In the alternated load tests the most striking feature was the relatively large slip which took place at comparatively low loads. The amount of this slip was especially large when a riveted joint had been subjected to a single load considerably beyond the ordinary load.

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*To determine the effect of painting the contact surfaces of riveted joints upon the load to give first noticeable slip, a phase of the subject brought out in correspondence with Mr. Albert Kingsbury, of Pittsburgh, Pennsylvania, tests for this purpose have been made since this bulletin was put in type. Joints resembling TB5 were riveted up, one set being unpainted, one set painted with graphite paint, and one set painted with red lead. All the riveted joints showed evidence of slip at loads within ordinary working shearing stress of rivets. Those painted with graphite paint gave noticeable slip at loads somewhat lower than those painted with red lead, and the unpainted test joints slipped at loads still a little higher, the differences in the three types of test joints being not large.

6. The ultimate shearing strength of riveted joints depends on the shearing strength of rivet material, and this is influenced by the relative hardness of rivets and plates.

7. The ratio of the yield point of riveted joint to ultimate shearing strength of riveted joint in the tests was about the same as the ratio of the yield point of the plate material in tension to the ultimate tensile strength of the plate material.

8. In riveted joints designed on the basis of ultimate strength, strength of rivet material and of plate material are of prime importance and the use of special steels of great strength may be of advantage.

9. In riveted joints designed on the basis of frictional hold of rivets without reference to the bending of rivets there is little advantage in using rivets of special steels of great strength since joints with such rivets show about the same resistance to first noticeable slip as do joints with ordinary carbon-steel rivets.

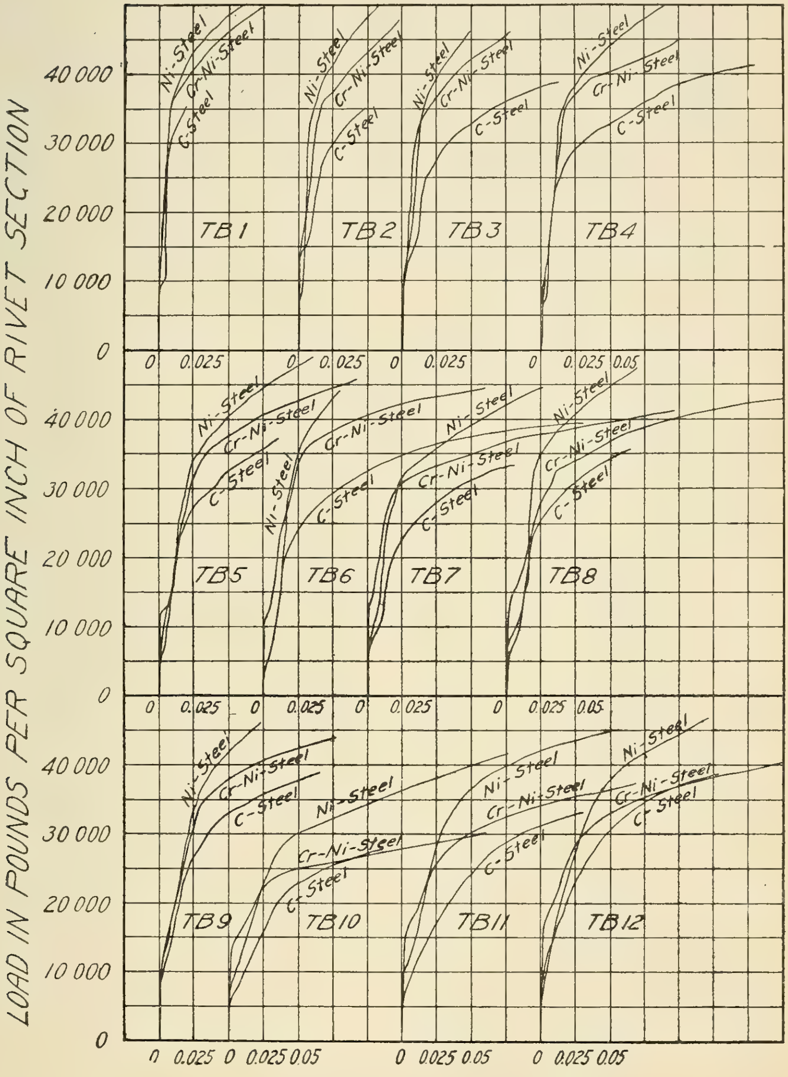

FIG. 17. DIAGRAM SHOWING PERMANENT SET IN TENSION TESTS.

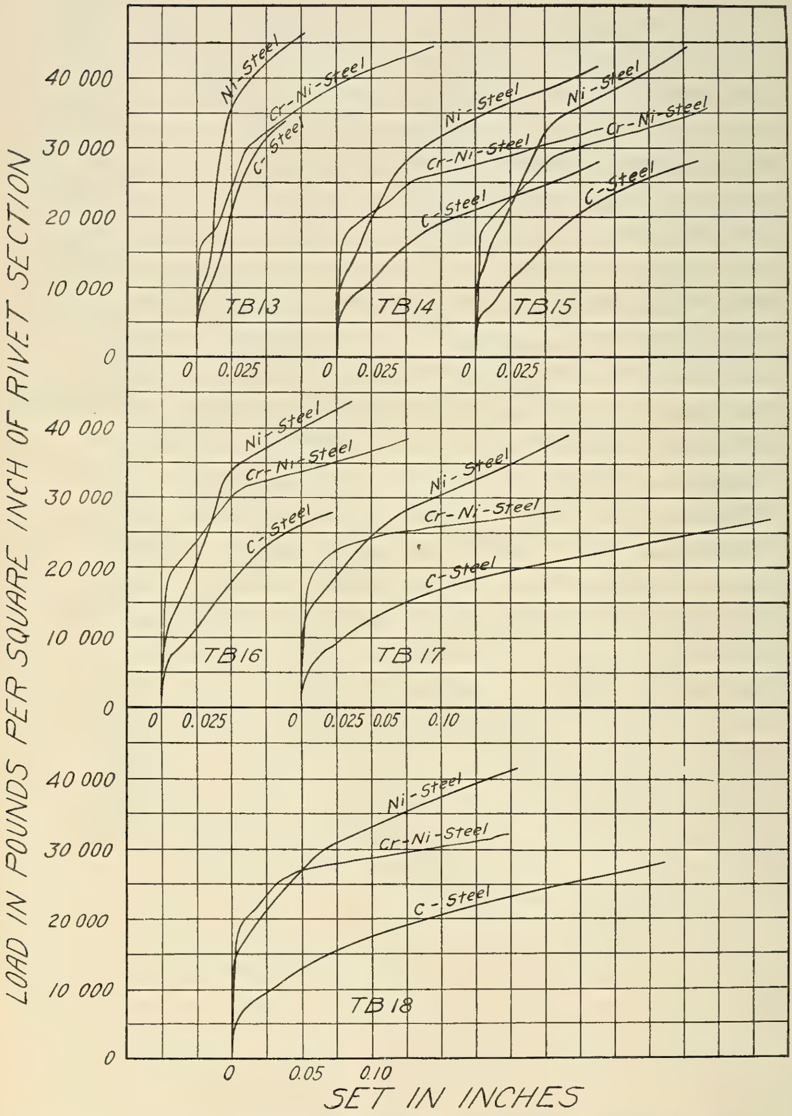

Fig. 18. Diagram showing Permanent Set in Tension Tests.

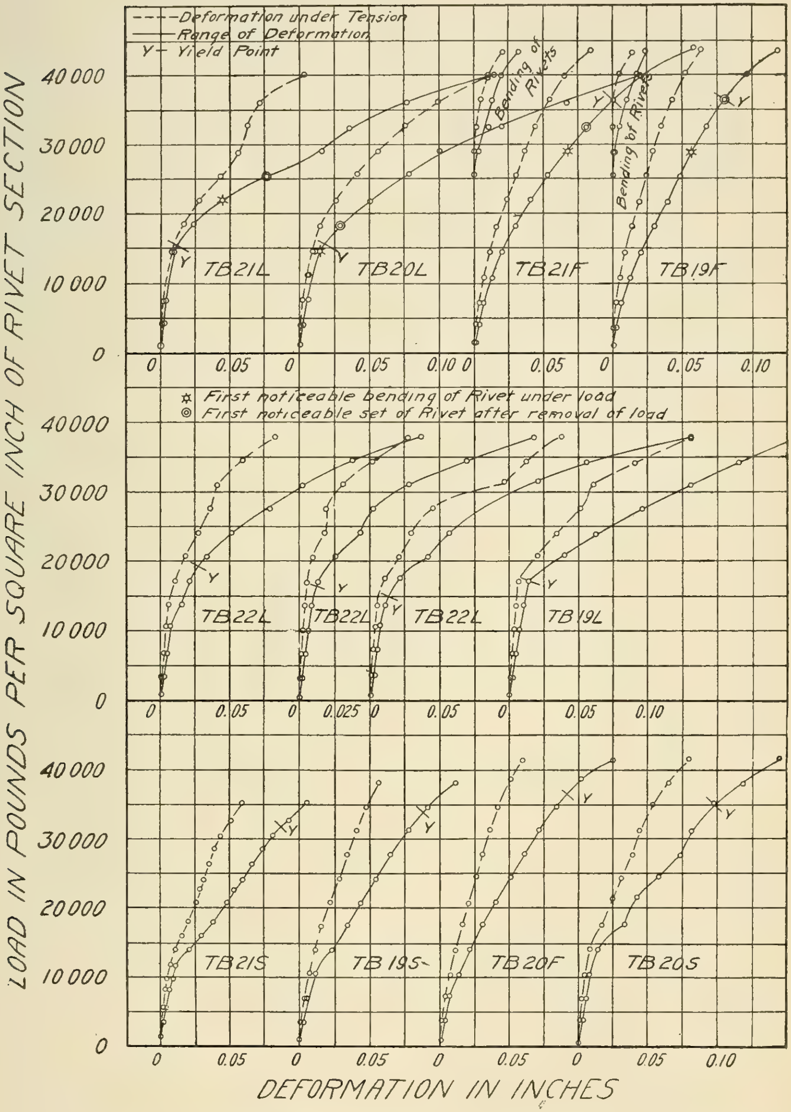

FIG. 19. DIAGRAM SHOWING DEFORMATION IN TESTS IN TENSION FOLLOWED BY EQUAL COMPRESSION.

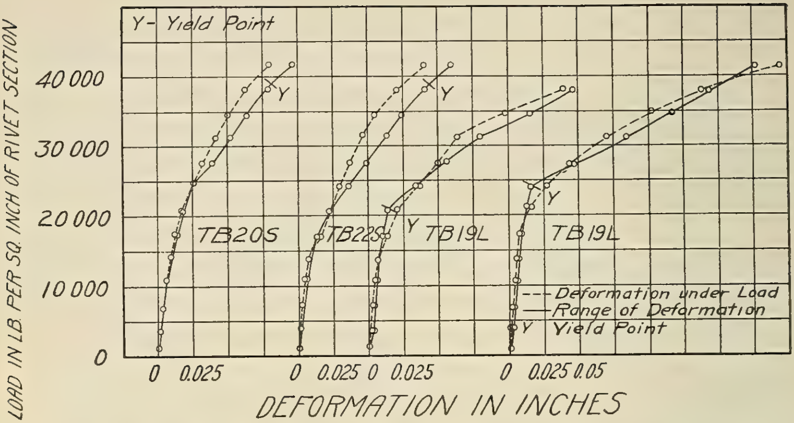

FIG. 20. DIAGRAM SHOWING DEFORMATION IN TESTS IN SIMPLE TENSION AND SIMPLE COMPRESSION OF RIVETED JOINTS DESIGNED FOR ALTERNATED LOADS.

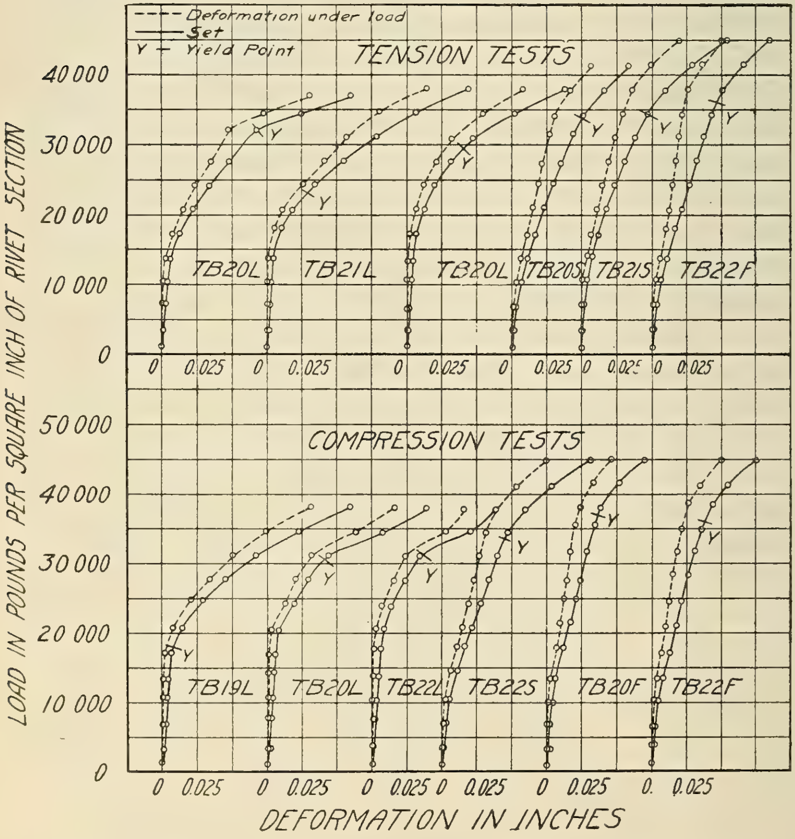

FIG. 21. DIAGRAM SHOWING DEFORMATION IN TESTS IN TENSION FOLLOWED BY HALF AS GREAT COMPRESSION.

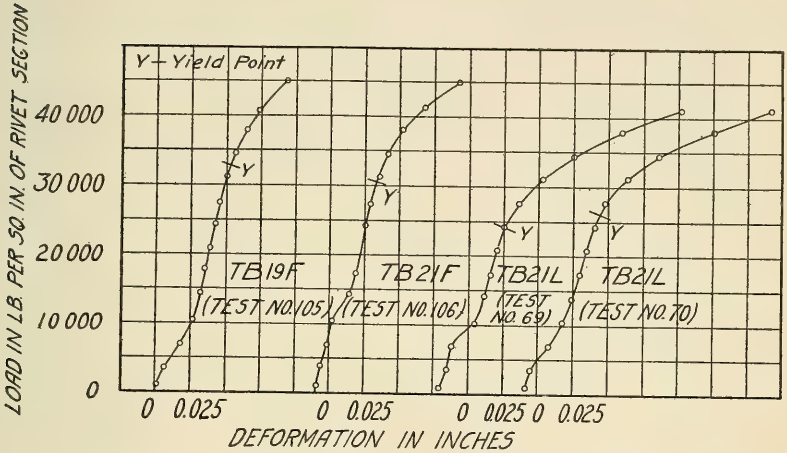

FIG. 22. DIAGRAM SHOWING DEFORMATION OF RIVETED JOINTS TESTED UNDER ALTERNATIONS OF LOW LOADS.

PUBLICATIONS OF THE ENGINEERING EXPERIMENT STATION

*_Bulletin No. 1._ Tests of Reinforced Concrete Beams, by Arthur N. Talbot. 1904.

*_Circular No. 1._ High-Speed Tool Steels, by L. P. Breckenridge. 1905.

*_Bulletin No. 2._ Tests of High-Speed Tool Steels on Cast Iron, by L. P. Breckenridge and Henry B. Dirks. 1905.

*_Circular No. 2._ Drainage of Earth Roads, by Ira O. Baker. 1906.

*_Circular No. 3._ Fuel Tests with Illinois Coal (Compiled from tests made by the Technologic Branch of the U. S. G. S., at the St. Louis, Mo., Fuel Testing Plant, 1904-1907,) by L. P. Breckenridge and Paul Diserens. 1909.

*_Bulletin No. 3._ The Engineering Experiment Station of the University of Illinois, by L. P. Breckenridge. 1906.

*_Bulletin No. 4._ Tests of Reinforced Concrete Beams, Series of 1905, by Arthur N. Talbot. 1906.

*_Bulletin No. 5._ Resistance of Tubes to Collapse, by Albert P. Carman. 1906.

*_Bulletin No. 6._ Holding Power of Railroad Spikes, by Roy I. Webber. 1906.

*_Bulletin No. 7._ Fuel Tests with Illinois Coals, by L. P. Breckenridge, S. W. Parr and Henry B. Dirks. 1906.

*_Bulletin No. 8._ Tests of Concrete: I. Shear; II. Bond, by Arthur N. Talbot. 1906.

*_Bulletin No. 9._ An Extension of the Dewey Decimal System of Classification Applied to the Engineering Industries, by L. P. Breckenridge and G. A. Goodenough. 1906.

*_Bulletin No. 10._ Tests of Concrete and Reinforced Concrete Columns, Series of 1906, by Arthur N. Talbot. 1907.

*_Bulletin No. 11._ The Effect of Scale on the Transmission of Heat through Locomotive Boiler Tubes, by Edward C. Schmidt and John M. Snodgrass. 1907.

*_Bulletin No. 12._ Tests of Reinforced Concrete T-beams, Series of 1906, by Arthur N. Talbot. 1907.

*_Bulletin No. 13._ An Extension of the Dewey Decimal System of Classification Applied to Architecture and Building, by N. Clifford Ricker. 1907.

*_Bulletin No. 14._ Tests of Reinforced Concrete Beams, Series of 1906, by Arthur N. Talbot. 1907.

*_Bulletin No. 15._ How to Burn Illinois Coal without Smoke, by L. P. Breckenridge. 1908.

*_Bulletin No. 16._ A Study of Roof Trusses, by N. Clifford Ricker. 1908.

*_Bulletin No. 17._ The Weathering of Coal, by S. W. Parr, N. D. Hamilton, and W. F. Wheeler. 1908.

*_Bulletin No. 18._ The Strength of Chain Links, by G. A. Goodenough and L. E. Moore. 1908.

*_Bulletin No. 19._ Comparative Tests of Carbon, Metallized Carbon and Tantalum Filament Lamps, by T. H. Amrine. 1908.

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TESTS OF A SUCTION GAS PRODUCER

BY

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AND

A. P. KRATZ

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UNIVERSITY OF ILLINOIS
ENGINEERING EXPERIMENT STATION

BULLETIN NO. 50 OCTOBER, 1911

TESTS OF A SUCTION GAS PRODUCER

BY C. M. GARLAND, FORMERLY INSTRUCTOR IN MECHANICAL ENGINEERING
AND A. P. KRATZ, INSTRUCTOR IN MECHANICAL ENGINEERING

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TESTS OF A SUCTION GAS PRODUCER

I. THEORETICAL DISCUSSION

1. *Introduction.*—The chemical reactions occurring within the fuel bed of the gas producer, while well understood by the metallurgist and the gas engineer, are probably not so clear to the mass of mechanical engineers. Hence, it may be pertinent in the presentation of the results of these tests, to review briefly the theory involved in the conversion of a solid fuel into a gaseous fuel through the agency of the gas producer.

2. *Simple Carbon Monoxide Producer.*—In its simplest form, the gas producer consists of a closed retort in which carbon is burned in a limited supply of oxygen. Fig. 1 illustrates such a producer. Air enters the retort at the base, and passing up through the grate into the bed of incandescent fuel, comes in contact with the carbon in the lower zone of the fuel bed, where the oxygen of the air unites with the carbon to form CO_2. The formula expressing this reaction is:

$$C + O_2 = CO_2 \ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

Since the atomic weights of carbon and oxygen are, respectively, 12 and 16, the above formula indicates that 12 parts by weight of carbon require 32 parts by weight of oxygen and that 44 parts by weight of carbon dioxide are formed; i. e.,

$$\begin{aligned} C + O_2 &= CO_2 \\ 12 + 32 &= 44 \\ \text{or} \quad 1 + 2\tfrac{2}{3} &= 3\tfrac{2}{3} \end{aligned}$$

This reaction is exothermic, i. e., it gives out heat, the amount of heat given out being 14 540 B. t. u. per lb. of carbon.

The CO_2 formed, remaining in contact with the incandescent carbon, begins immediately to take up more carbon, since at temperatures above 1100°F., the CO_2 becomes an oxidizing agent. This reaction is expressed by the formula:

$$CO_2 + C = 2\,CO \ldots\ldots\ldots\ldots\ldots\ldots (2)$$

which is reversible, i. e., it may take place in either direction, depending upon the temperature.

The above formula shows that 44 lb. of CO_2 unite with 12 lb.

of C and produce 56 lb. of CO. Thus:

$$\begin{gathered} CO_2 + C = 2\ CO \\ 44 + 12 = 56 \\ 3\tfrac{2}{3} + 1 = 4\tfrac{2}{3} \end{gathered}$$

This reaction is endothermic, i. e., it absorbs heat from the fuel bed. The amount of heat absorbed per pound of carbon taking place in the reaction is 10 100 B. t. u.

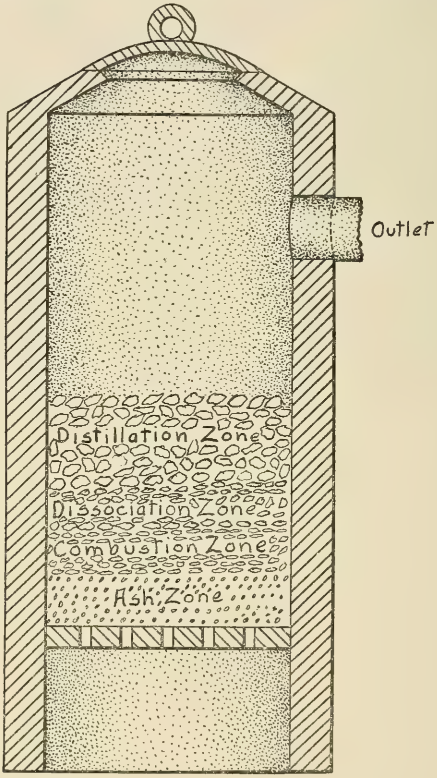

FIG. 1

As the 10 100 B. t. u. represents also the amount of heat that would be given out on combustion of the CO formed, the theoretical thermal efficiency of the carbon monoxide producer will be, therefore, if all of the carbon is assumed to be converted into carbon monoxide, $\frac{10100}{14540} = 69.5$ per cent. The remaining 30.5 per cent of the heating value of the fuel has been lost in radiation, conduction, and in sensible heat in the gases leaving the producer. The gas will consist of CO and N_2.

3. *Producer Using Water Vapor.*—In the actual commercial producer, the loss in sensible heat inherent in the simple carbon monoxide producer is reduced by utilizing this heat in the decomposition of some other agent, either the vapor of water or carbon dioxide, introduced into the fuel bed with the air. The water vapor is usually supplied by evaporating water either in an external boiler, which utilizes the sensible heat of the gases leaving the producer, or by some form of vaporizer in the form of a water jacket surrounding the fuel bed, and utilizing the heat from the fuel bed for the vaporization of the water. The steam generated in either case mixes with the air entering the producer, and passes with it into the fuel bed.

The reaction between the carbon and oxygen of the air has been considered, and it has been pointed out that for each pound of carbon burning to carbon dioxide, 14 540 B. t. u. was given out; also, that if this carbon dioxide were decomposed into the monoxide, its formation would take up 10 100 of the B. t. u. originally given out. Consequently, 4440 B. t. u. would be left in the form of sensible heat, part of which might be utilized in the decomposition of water into oxygen and hydrogen. The hydrogen liberated through such a reaction would pass through the fuel bed partially intact, thus adding a combustible constituent to the gas, while the oxygen would unite with the carbon to form either the dioxide or the monoxide, depending upon the temperature at which the reaction occurred. It is considered, ordinarily, that the following reactions occur within the producer when the vapor of water is introduced with the air, viz:

$$2\,H_2O+C=2H_2+CO_2 \quad \dots\dots\dots\dots\dots\dots (3)$$

and

$$H_2O+C=H_2+CO \quad \dots\dots\dots\dots\dots\dots (4)$$

Reaction 3 predominates in the region of low temperatures between 1000° and 1600° F. Above 1600° F., reaction 4 predominates. At a temperature close to 1000° F., there will scarcely be a trace of reaction 4. If it is considered that the fuel bed is of a uniform temperature, in the neighborhood of 1000° F., so that reaction 3 holds, the following relation exists between the constituents entering into the reaction.

36 lb. of water + 12 lb. of carbon produce 4 lb. of hydrogen and 44 lb. of carbon dioxide, i. e.,

$$2H_2O + C = 2H_2 + CO_2$$
$$36 + 12 = 4 + 44$$

or

$$3 \ + 1 = \tfrac{1}{3} + 3\tfrac{2}{3}$$

and 1 lb. of carbon burning to CO_2 liberates 14 540 B. t. u.,
1 lb. of hydrogen burning to H_2O liberates 62 000 B. t. u.

Since $\frac{1}{3}$ lb. of hydrogen is formed through this reaction, $\frac{62\,000}{3} =$ 20 660 B. t. u. disappears or is absorbed. For each pound of carbon entering into the reaction, $20\,660 - 14\,540 = 6120$ B. t. u. disappears. Evidently, the above heat deficit must be supplied by additional carbon in the fuel bed burning to CO_2 through the presence of oxygen supplied in the air and according to reaction (1) $C + O_2 = CO_2$, since for the assumed temperature of the fuel bed, it will not be possible for more than a trace of the carbon monoxide to form.*

From equation (1), 14 540 B. t. u. is liberated per pound of carbon, therefore $\frac{6120}{14540} = .42$ lb. additional carbon, burned to CO_2, is necessary to supply heat for the completion of reaction 3. Consequently, 1.42 lb. of carbon are necessary for the formation of $\frac{1}{3}$ lb. of hydrogen, all of the heat of the carbon being utilized in the production of hydrogen, which is the only combustible constituent of the gas, the other constituents being CO_2 and N_2.

In considering reaction 4, which predominates at the higher temperature, it will be well to refer again to the experiments of Harries.

---

*Haber's "Thermodynamics of Technical Gas Reactions", page 138.

This has been illustrated very clearly by the experiments of Harries. Harries passed water vapor over incandescent carbon in a tube at various temperatures and found the relation between the CO, CO_2, H_2O and H_2 in the resulting gas. At a temperature of 1240° F., the following results were obtained:

H_2 per cent = 8.41; CO_2 per cent = 3.84; CO percent = 0.63; H_2O per cent = 87.12

The extent of this reaction, doubtless, depends not only upon the temperature, but also upon the time of contact of H_2O and CO_2 with the carbon, and while the latter variable has evidently been neglected in the experiments, the results are sufficiently decisive to justify the above assumption that at the low temperature, the percentages of CO formed will be a negligible quantity.

At a temperature of 2050° F., the following relation was found between the constituents of the gas leaving the tube,

$$\begin{aligned} H_2 \text{ per cent} &= 50.730 \\ H_2O \text{ per cent} &= 0.303 \\ CO_2 \text{ per cent} &= 00.600 \\ CO \text{ per cent} &= \underline{48.340} \\ & 99.973 \end{aligned}$$

This clearly illustrates the predominance of reaction 4.

If it is assumed again that the temperature throughout the fuel bed is uniform and is such that only reaction 4 occurs, we have

18 lb. water + 12 lb. carbon producing 2 lb. hydrogen and 28 lb. CO

or

$$H_2O + C = H_2 + CO$$
$$18 + 12 = 2 + 28$$

or

$$1\tfrac{1}{2} + 1 = \tfrac{1}{6} + 2\tfrac{1}{3}$$

1 lb. of carbon burning to CO liberates 4440 B. t. u.,

and

1 lb. of hydrogen burning to H_2O liberates 62000 B. t. u.

Consequently, the formation of $\frac{1}{6}$ lb. of hydrogen absorbs $\frac{62000}{6}$ = 10330 B. t. u. A deficit of 10330 — 4440 = 5890 B. t. u. results. This may now be made up by carbon burning to CO through the oxygen supplied in the air according to reactions 1 and 2. For each pound of carbon burning to CO 4440 B. t. u. is liberated. Consequently, in order that reaction 4 be completed, $\frac{5890}{4440}$ = 1.33 lb. of carbon must burn to CO. The total heat from the burning of 2.33 lb. of carbon to CO results in the production of $\frac{1}{6}$ lb. of hydrogen. $1\frac{1}{2}$ lb. of water are theoretically necessary, or .64 lb. of water per lb. of carbon.

The gas resulting from the above reactions consists of CO, H_2, and N_2. The percentage by volume may be obtained in the following manner:

Total weight of $H_2 = \frac{1}{6}$ lb.
Total weight of $CO = 2.33 \times 2\frac{1}{3} = 5.44$

Total volume of H_2 at 62° F. and 30 in. Hg. $= \frac{1}{6} \div 0.0053 = 31.5$ cu. ft.
Total volume of CO at 62° F. and 30 in. Hg. $= 5.44 \div 0.0736 = 74.00$ cu. ft.
Total volume of O_2 from air $1\frac{1}{3} \times 1.33 \div .0842 = 21.1$ cu. ft.
Total volume of air $21.1 \div 0.21 = 100.3$ cu. ft.
Total volume of N $=79.2$ cu. ft.
Total volume of gas leaving producer $31.5 + 74 + 79.2 = 184.7$ cu. ft.
Total volume of gas per lb. of carbon $184.7 \div 2.33 = 79.3$ cu. ft.

Theoretical Gas Analysis	High Heating Value B. t. u. per cu. ft.
H_2 per cent = 17.0	55.8
CO per cent = 40.0	127.8
N_2 per cent = 43.0	000.0
total	183.6

4. *Conditions in the Actual Producer.*—In the actual producer, reactions 3 and 4 are doubtless taking place continuously in different parts of the fuel bed. It would hardly be possible to operate a producer at so low a temperature as to produce the results obtained according to reaction 3. It would be impossible to operate at such a temperature as to prevent reaction 3 occurring.

The conditions that probably maintain are as follows. The moisture laden air, comparatively cool, passes into the fuel bed; on entering, it cools down the first layer of fuel, or the combustion zone, as it is usually called, to such an extent that reactions 1 and 3 probably result, part of the oxygen supplied by the air uniting with the carbon to form CO_2, while part of the moisture decomposes and forms H_2 and CO_2.

The carbon dioxide, formed according to reactions 1 and 3, passes up into the hotter portion of the fuel bed and takes up other atoms of C to form CO, according to reaction 2. The moisture which is not decomposed and the O_2 which is not combined in the combustion zone pass into the hotter portion of the fuel bed known as the decomposition zone, or dissociation zone, where reactions 1 and 2 probably take place in immediate succession, in the case of the oxygen, while part of the moisture is combined according to 4, producing H_2 and CO. The gases leaving this portion of the fuel bed are therefore composed of H_2, CO, CO_2 and small quantities of O_2, and vapor of water, the last two constituents having either passed through the fuel bed intact or having resulted from dissociation. Theoretically, at the higher temperatures there should be only a trace of CO_2; actually, this quantity will vary from 2 to 17 per cent of the volume of the gas, depending upon a number of conditions. The gases passing from the dissociation zone or layer of high temperature enter into the distillation zone, which is at a lower temperature, and which is so named for the reason that in this zone the volatile matter is distilled from the fresh fuel by the hot fuel bed beneath. This volatile matter for anthracite coal consists of small quantities of H_2, H_2O, CH_4, C_2H_4 and condensible hydrocarbons in the form of tar, etc. The CH_4 and C_2H_4 in the producer gas made from anthracite are inconsiderable; the former will not represent more than 2 per cent of the volume of the gas, while the C_2H_4 will probably not exceed 0.1 per cent by volume. The condensible hydrocarbons are also inconsiderable.

In producer gas made from bituminous coal, these distillation products may represent 40 per cent of the heating value of the gas, and are not only desirable but necessary constituents, when the gases are to be used for reverberatory and other metallurgical furnaces where high temperatures are desirable.

The following reaction, which may occur between the constituents of producer gas, is reversible and depends upon the temperature.

$$CO + H_2O = CO_2 + H_2 \quad \ldots\ldots\ldots\ldots (5)$$

From the results of Hahn's[1] investigations, it was shown that at a temperature of 1520° F., H_2 and CO became equally strong reducing agents. At lower temperatures, the carbon monoxide is the stronger. This means that if the gases on leaving the dissociation zone enter a zone at a temperature lower than 1520°, there will be a tendency for the CO to react on the water vapor present and form CO_2 and H_2. At higher temperatures, there will be a tendency toward the formation of CO and water. The velocity of the reaction and the extent to which each takes place depend upon the temperature and the depth of the fuel bed. High temperatures and deep fuel beds tend to produce a gas low in CO_2 and H_2. Low temperatures or shallow fuel beds produce a gas low in CO, and high in CO_2 and H_2.

It should be understood that the above reactions depend very largely upon the presence of the fuel which acts as a catalyst. Allner[2] has shown that if the above reaction in the presence of a catalyst is established, or if equilibrium maintains at a temperature above 2200° F., and if the gases are cooled without the presence of the catalyst, the reactions are "frozen", that is, the removal of the catalyst does not permit the readjustment of equilibrium due to the lower temperature that would otherwise have occurred had it not been removed. If, on the other hand, the catalyst is not removed and the gases are cooled, the reaction will continue until a temperature of about 1400°F. is reached. This latter is the condition that maintains in the producer as the gases flow from the dissociation zone to the distillation zone. The extent of this reaction depends upon the velocity of the gases through the distillation zone, the depth of this zone, and upon the temperatures within the zone. After the gases have left the zone, i. e., are out of the presence of the catalyst, the reaction is "frozen", and no further change in the composition of the gas occurs.

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[1] Haber: Thermodynamics of Technical Gas Reactions, page 145.
[2] Haber: Thermodynamics of Technical Gas Reaction, page 309.

5. *The Carbon Monoxide Producer.*—The simple carbon monoxide producer has been considered in the discussion of the theory of the producer. In contradistinction to this, there is a commercial producer known as the carbon monoxide producer, which is being used to some extent. The differentiation of this producer from other commercial producers lies in the substitution of CO_2, taken from some outside source, for the vapor of water, for the purpose of conserving part of the 30 per cent heat loss inherent in the simple carbon monoxide producer. The producer is used principally for the driving of gas engines. The supply of CO_2 is obtained by piping the exhaust from the engine to the ashpit of the producer.

From reactions 1 and 2, and when one pound of carbon burns to CO, it is known that 4440 B. t. u. is given out, which may be utilized in the dissociation of CO_2. 14 540 B. t. u. is liberated per pound of carbon entering into the reaction, and since in the production of CO, 4440 B. t. u. is liberated, evidently 10 100 B. t. u. remains in the CO. Therefore, in the reduction of CO_2, 10 100 B. t. u. is absorbed per pound of carbon entering into the reaction, while $\frac{10100}{3\frac{2}{3}} = 3966$ B. t. u. is absorbed per pound of CO_2. The

B. t. u. free for the carrying out of this reaction per pound of carbon is 4440. The number of pounds of CO_2 necessary for the utilization of this heat is $\frac{4440}{3966} = 1.11$ lb. Since each pound of carbon in the producer appears principally as CO_2 in the exhaust gas of the engine, there will be $3\frac{2}{3}$ lb. of CO_2 produced in the exhaust per lb. of carbon in the producer which is much more than is necessary for the above reaction.

On investigation, this system would seem to offer a number of advantages over the system in which the producer uses steam for the production of H_2. The gases leaving the producer consist principally of CO and N_2, together with small quantities of H_2, CH_4, and C_2H_4, distilled off from the green fuel. The gas, therefore, will be likely to be more uniform in quality than H_2 enriched gas, and will, consequently, be less likely to cause premature ignition in the engine cylinder. This will be due to the large quantity of nitrogen present in the gas and to the small quantity of hydrogen. It will also be possible to use a much higher compression in the engine cylinder, and this will tend to offset any loss in efficiency in the producer that may be caused by the sensible heat lost in the nitrogen. Since part of the engine exhaust is delivered to the producer, the sensible heat in the exhaust is utilized in addition to the heat contained in the unburned products resulting from incomplete combustion in the engine cylinder. These latter may represent anywhere from 5 to 20 per cent of the heating value of the original gas. The disadvantage of the process doubtless lies in the regulation of the amount of CO_2 delivered to the producer.

II. Purpose of the Tests and Discussion of the Methods of Experimentation

6. *Object of the Tests.*—In the field of small isolated power plants, the suction gas producer using anthracite coal of the finer grades has for the past few years been fighting for place. As in the case of almost all new apparatus, its ultimate success or failure has been retarded largely on account of the lack of impartial data on the efficiency, cost of operation, reliability, etc., together with the natural prejudices against change, and the difficulty in

securing capable operators. The tests herein described were made for the purpose of obtaining impartial data on the efficiency, reliability, and operation of suction gas producers of small size, using anthracite coal as fuel. They were conducted on the producer in the Mechanical Engineering Laboratory, of the University of Illinois. Incident to the main object of the tests was the development of a method of studying and testing the producer, the standardization of forms for the presentation of the results of the tests, and probably the most important of all, the derivation of formulas for the necessary computations. Twenty-five tests were made and four grades of fuel used. The results of all tests are included in Table 5, and the forms and formulas are given in the Appendix.

It is hoped that the results of the tests themselves will be of value to manufacturers and to users of small power; the method and forms, a partial discussion of which has appeared in a previous article[1], may be of value to builders of gas producers and to engineers engaged in development and testing.

7. *The Producer.*—The producer under consideration was installed by the Otto Gas Engine Works of Philadelphia, and is known as their No. 3 producer. In the specifications, it was stated that the producer had a maximum capacity of supplying gas for 60 horse-power, and that this was equivalent to a maximum production of 8100 cu. ft. of gas per hour. It was also stated that the producer was designed for intermittent operation and that the length of runs should not be greater than 12 hours.

TABLE 1

Dimensions and Proportions

1.	Dimensions of grate, ft.	1.25 x 1.33
2.	Grate area, sq. ft.	1.666
3.	Mean diameter of fuel bed, ft.	1.545
4.	Depth of fuel bed, ft.	2.21
5.	Area of fuel bed, sq. ft.	1.877
6.	Height of discharge pipe above grate, ft.	2.875
7.	Approximate width of air spaces in grate, in.	0.5
8.	Area of air space, sq. ft.	0.722
9.	Proportion of air space to whole grate area, per cent	43.3
10.	Area of discharge pipe, sq. ft.	.165
11.	Outside diameter of shell, ft.	2.833
12.	Length of shell from base to top of magazine, ft.	7.125
13.	Ratio of minimum draft area to grate area, 1 to	48.8

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[1] Journal A. S. M. E., Dec. 1909.

The producer, the principal dimensions of which are given in Table 1, was of the contained vaporizer type and was provided with a plain bar grate.

The plant, as installed by the Otto Gas Engine Works, consisted of the producer, a wet scrubber, a gas receiver and a 23 horsepower producer gas engine known as their No. 7 engine. A section through the producer is shown in Fig. 2. A diagrammatic sketch of the plant as modified for testing is shown in Fig. 3.

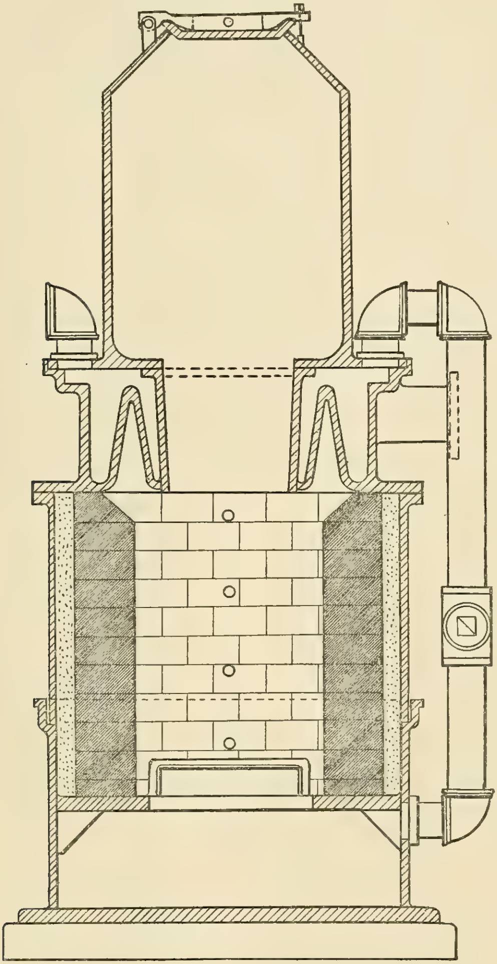

FIG. 2

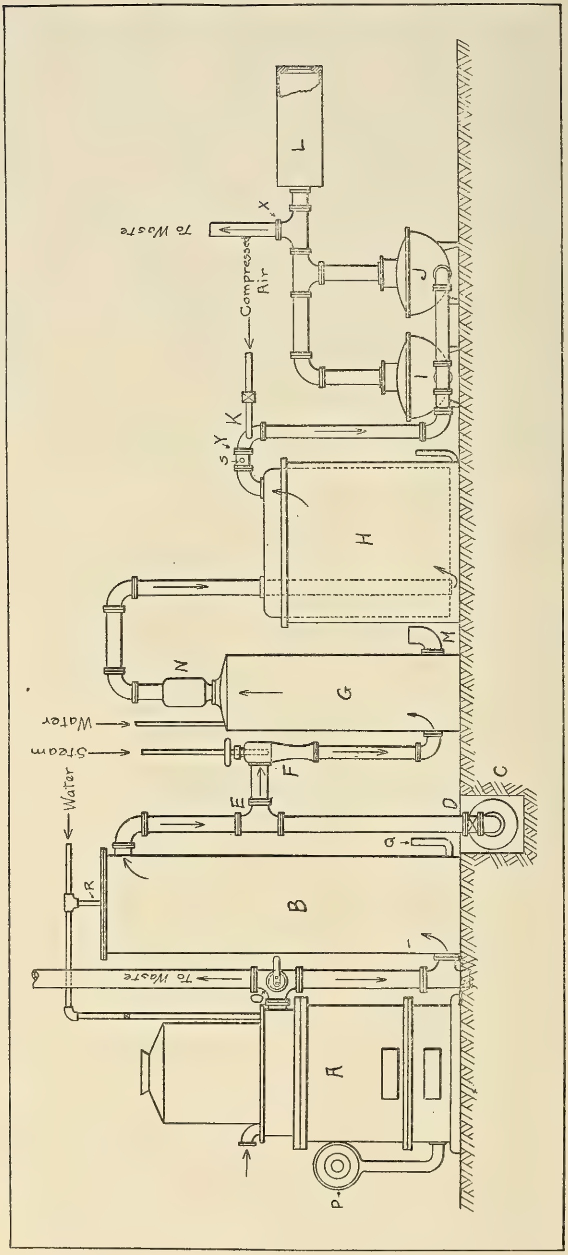
P
A
To Waste
O
Water
R
B
Q
D
C
E
F
Steam
Water
G
M
N
H
S
Y
K
Compressed Air
I
J
X
To Waste
L

Fig. 3

In order to relieve the producer test of an engine running in conjunction with it and to make the former independent of the latter, it was decided to blank off the engine from the gas main and produce the necessary suction by means of a steam ejector. This reduced the labor of operating to minimum, made regulation positive, under immediate control, and produced conditions tending to insure greater accuracy and satisfaction.

It has been urged that producer tests can not be run like boiler tests, independently of the engine, principally on account of the prejudice existing among prospective buyers of producer installations. This objection would doubtless hold in the case of acceptance tests, but even so, it would be desirable in all such cases to run the engine tests in conjunction with the producer tests, and under the normal conditions of everyday operation.

However, for the purpose of studying the producer when operating under different conditions, or for studying the action of different fuels in the producer, or for obtaining data on the efficiency and composition of the producer gas generated, the present method has decided and obvious advantages.

8. *The Plant.*—Referring to Fig. 3, the producer A is shown, provided with a fan blower P for starting, a two-way cock O, a waste pipe leading to the roof and a water seal in the connection between the producer and the first wet scrubber B. The wet scrubber B was filled with coke and provided with an overflow at Q. The scrubber water entered at R. The Schutte-Koerting steam ejector used for producing the draft, was located at F and provided with the steam connection as indicated. The ejector has a capacity of 12 000 cu. ft. of gas per hour. The steam used by the ejector is condensed in the second wet scrubber G and the suspended moisture is removed by the separator N and the dryer H. The latter is simply a gas bell filled with straw. Its use was made necessary by the Westinghouse meters located at I and J. These meters are of the "wet" type, so that the suspended moisture in the gases, before the use of the dryer, tended to collect in the meter and raise the level of the sealing fluid. The gauge box L was blanked off from the pipe line during the producer tests and was used only for the calibration of the meters. This calibration was effected by the use of air introduced at the compressed air connection indicated.

9. *Method of Conducting the Tests.*—In conducting the tests,

the items to be considered first were the weight of coal, the heating value of the coal, the volume of gas, and the heating value of the gas. The measurement of these quantities will be considered in the order named.

(1). *Determining the Weight of Coal Fired.*—The correct determination of the weight of coal fired in testing producers of the intermittent type, where tests of short duration are necessary, is a problem of no small importance, owing to the difficulties in obtaining the weight of coal in the producer at the start and at the close of the test. The method of starting that suggests itself as being the most readily carried out, especially by the engineer, is to clean the ash and clinker out and work the fuel bed, by means of the poking bar, into a uniform condition; then, in closing, to duplicate these conditions as nearly as possible.

In any actual case, it is always possible to compute from a number of actual trials the average weight of coal required to fill the producer to a given level. If this mean value is taken as the true value or true weight of coal required to fill the producer, then the maximum variation from the mean or true value in the case of any one trial will indicate the probable maximum error that will be made in filling the producer. Evidently this same maximum error may be made in bringing the fuel bed to the starting condition, irrespective of the weight of coal required to bring the fuel bed to this condition. An example will illustrate this better. Suppose that for a number of actual trials, the average weight of coal required to fill the producer to a given level is 600 lb.,—suppose the maximum variation from the mean is 15. The maximum error is 2½ per cent, based on 600 lb. Suppose, further, that in a given test, 200 lb. of coal were burned. Evidently in bringing the fuel bed to the starting condition and in filling, a maximum error of 15 lb. may be made; i. e., in filling, it is possible to make an error in this particular test of 7½ per cent.

In order to determine the error approximately in estimating the weight of coal during the present tests, the producer was filled four separate times, and the weight of coal required noted in each case. The average of the four weights was taken as the mean weight or true weight of coal required to fill the producer. The results are given in Table 2.

It will be seen from this table that the maximum variation from the mean is 8.75 lb. or 1.7 per cent. It will be seen from Table 5, giving the results of the tests, that the smallest weight of coal fired on any test was for test 26, and that this weight was 146 lb. In bringing the fuel bed to starting conditions and in filling the producer at the close of the test, it would, therefore, have been possible to make an error of 8.75 lb., or, in this case, an error of $\frac{8.75 \times 100}{146} = 6$ per cent. This is, of course, the purely mechanical error in filling, and does not take into consideration the difference that may maintain in the condition of the fuel bed in starting and stopping. There is always present in the fuel bed a larger per cent of ash in stopping than in starting, and if this is in the form of clinker, a large error may result. If it is in the form of a powder, the error will probably not be so great, as the ash will tend to pack into the interstices around the coal; and while the fuel bed may contain a larger per cent of ash in stopping than in starting, the volume of the fuel bed, and the weight of carbon present may remain practically the same. The error, therefore, in the estimation of the weight of coal due to the presence of the ash will not be large. The error in determining the weight of ash is unimportant, as this may be determined from the analysis of the coal and the total weight of coal fired, with a greater degree of accuracy than could possibly be determined from the weight of the ash and refuse taken from the producer.

TABLE 2

WEIGHT OF GREEN COAL REQUIRED TO FILL THE PRODUCER

Trial No.	Weight pounds	Variation from Average Weight	Variation per cent
1	669.25	8.75	1.70
2	676.25	1.75	.26
3	683.25	+5.25	.77
4	683.25	+5.25	.77
Total	2 712.00		
Aver.	678.00		

The above method of starting and stopping the test has been used throughout the present work. There is another and much more accurate method of procedure, which is, however, both tedious and expensive. Fill the producer with a weighed amount of wood and coal and start the fire. During the period of starting, measure the volume of gas discharged, and at the same time take a continuous sample for analysis. Also weigh the ash and refuse accumulating during this period, and take a sample for analysis.

Reduce the total volume of gas to standard gas, i. e., gas at 62° F. and 30 in. Hg., and calculate from the analysis the volume of CO_2, CO, H, CH_4 and C_2H_4. From the specific weights of the constituents of producer gas as given in the Appendix page 84, item 121, calculate the total weight of each of these constituents. Let a, b, c, d, e, be the weights of the respective constituents. Then the total weight of carbon that has been taken from the fuel bed during the starting period will be,

$$W = \tfrac{3}{11}a + \tfrac{3}{7}b + \tfrac{3}{4}d + \tfrac{6}{7}e + w_1$$

where w_1 = the total weight of carbon as determined from the analysis and the weight of the ash and refuse.

The total weight of hydrogen that has been taken from the fuel in the producer and that appears in the gas may be determined by the formula

$$W_2 = c + \tfrac{1}{4}d + \tfrac{1}{7}e$$

This neglects the hydrogen that may be formed by the decomposition of water, and will, therefore, introduce an error, the amount of which will depend upon the length of time between the lighting of the fire and the starting of the test. With small producers, this will be very small. In large producers, tests are usually of such length and the weight of coal fired of so large an amount, as to make the error in the estimation of the coal in starting and stopping a negligible amount, consequently, such a method as the one under discussion would not be necessary.

In closing the test, the coal should be burned low in the producer, and immediately after closing, the fuel bed should be drawn and weighed, the incandescent coals quenched and then sampled, and an analysis made from the sample.

The total weight of equivalent coal fired during the test may be obtained from the following formula,

$$W_c = W_s + W_t - \frac{(W + W_f)\,14\,560 + W_2 \times 62\,000}{H}$$

where

W_c = total weight of equivalent coal fired during the test.
W_s = total weight of equivalent coal in producer at the start.
W_t = total weight of coal fired during test.
W = total weight of carbon appearing in the gas before starting.
W_2 = total weight of hydrogen appearing in the gas before starting.
W_f = total weight of carbon within the fuel bed at the close of test.
H = The heating value of the coal per pound.

(2) *Heating Value and Analysis of the Coal.*—The heating value and the analysis of the coal were determined by the chemist, and a discussion of the chemical method is unnecessary here. The chemical work is probably accurate within one per cent. The greatest error in the analysis or in the heating value is likely to be made in the sampling of the coal. The weight of the coal sample should be not less than 10 per cent of the total weight of coal fired, and the samples taken in the present tests represented from 10 to 15 per cent of the weight of coal fired. These samples were mixed and quartered until a sample sufficient to fill about eight quart jars was obtained; this sample was then reduced by grinding until it would pass a $\frac{1}{4}$ in. screen. This was again mixed and quartered, and a sample taken sufficient to fill a pint jar. This sample was sent to the chemist for analysis.

The coal used in the tests was stored indoors and was practically air-dry as fired. Proximate analyses and heating values were obtained from the coal used in every test. Ultimate analyses were obtained for at least three samples from each grade of coal used. From these ultimate analyses and the proximate analyses from each test, the ultimate analysis for each test was determined by a method of approximation.

(3) *Measuring the Volume of the Gas.*—The volume of the gas generated was measured by Westinghouse meters. These were of the wet type, so that the gas should contain no suspended moisture. This moisture was removed by the dryer shown in Fig. 3. In order to insure accuracy in the measurement by the meters, a gauge box *L*, Fig. 3, was connected to the gas main so that the meter or meters could be calibrated from time to time. This calibration was effected by the use of compressed air. Blind flanges were

placed at *X* and *Y*, and the air was admitted at the connection shown. This air, expanding, passed to the meter and then to the gauge box which contained a thin plate orifice. The pressure and temperature of the air were taken at the meter and also at the gauge box. From the pressure and temperature in the gauge box the volume of air passing the orifice was computed from the work of R. J. Durley.[1] From this volume, and the pressure and temperature taken at the meter, the volume passing the meter was computed.

The calibration was made at different capacities and a calibration curve for the meter plotted. This latter was practically a straight line.

In obtaining the volume of gas generated during a test, the volume was taken from the calibration curve of the meter and then reduced to standard gas by the formula given on page 86, of the Appendix, item 125. The volume of gas as obtained from the meter, as just explained, was checked by calculating the volume of gas generated from the weight and analysis of fuel and the analysis of the gas. The formula for this computation is given in the Appendix, page 86, item 126.

The volumes as obtained by computation ordinarily checked within 5 per cent of the volumes determined by the meters. Where the sampling of coal and ash is carefully carried out, this method of computing the volumes from the analysis is reliable for producers using hard coal. It is based on the fact that the weight of carbon contained in the coal must equal the weight of carbon contained in the gas plus the weight contained in the ash and refuse, plus the weight lost in tar and the weight lost in the gas absorbed by the scrubber water. The carbon lost from the hard coal producers in the form of tar and condensible hydrocarbons is very small, doubtless less than one per cent. The weight lost by the absorption of CO_2 and CO in the scrubber water is also very small, so that the carbon in the coal should be accounted for within 5 per cent at the most. The method may even be used for the determination of the volume of gas generated by bituminous coal producers. In the case of these producers, 10 per cent of the carbon may be lost in the tar and other heavy hydrocarbons which condense and are deposited in the scrubbers and gas mains.

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[1] Trans. American Society Mechanical Engineers, Dec. 1905.

The percentage of carbon so lost may be found by taking a continuous sample of the gas as it leaves the producer, and before it is cooled, and drawing it through some form of condenser in which the condensible matter will be thrown down while the gas passes to a small meter for measurement. From the weight and analysis of the condensed matter and the volume of the gas sample, the per cent of carbon lost in this way may be obtained. The determination is tedious and requires considerable outlay, but it may often be used to advantage in the testing of large producers where mechanical means of measuring the volume of the gas generated are impossible. The value of the volume of gas computed from analysis as a check on the accuracy of the test has been discussed on page 39.

(4) *Sampling the Gas*[1].—The correct sampling of the gas for analysis and for the determination of the heating value is imperative. In the present tests, the form of sampling device is illustrated in Fig. 4. This device takes the sample from three separate points in the main and practically the same volume of gas from each point. In mains of larger diameter, more nipples should be used. A good rule is to use one sampling nipple for each inch of diameter of main.

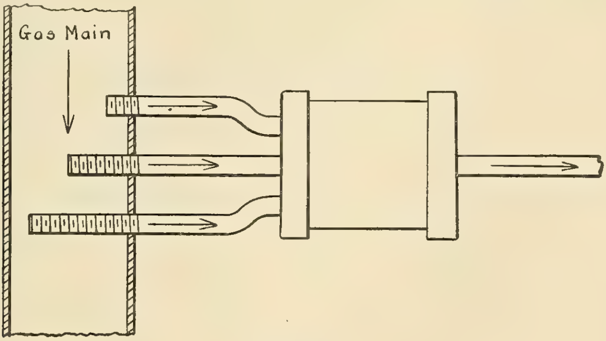

FIG. 4

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[1] Credit is due Mr. O. A. Carnahan for his painstaking and conscientious work in the analysis of the gases, for all the tests, and his ingenuity and suggestions along this particular line. Credit is also due Mr. J. P. Clayton for his assistance in computing, and in operating the calorimeter on a large number of tests.

The above device was inserted beyond the second scrubber and at *S*, Fig. 3. In this position, the gas is under pressure so that it is necessary only to connect the aspirator bottle used for collecting the sample of gas to the nipple leaving the sampling device.

Where the gas is under a pressure lower than atmospheric, it is necessary to connect an aspirator of the ordinary laboratory type to the sampling device and draw the gas from the main by the aspirator and force it into a vessel provided with a water seal. Samples of the gas may be taken from this vessel both for analysis and for the calorimeter. Fig. 5 illustrates the arrangement. The principal objection to its use is that small quantities of gas, principally CO_2, are absorbed by the water in the aspirator.

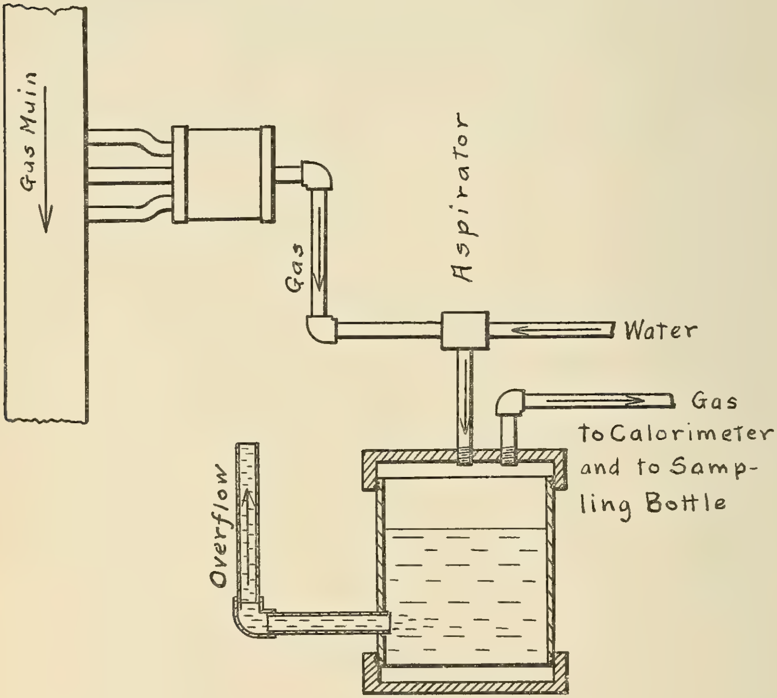

FIG. 5

The sample of gas taken from the sampling device for analysis was collected for the present tests in ordinary aspirator bottles and over water previously saturated with producer gas. These bottles held about 5 litres. 600 cc. of the sample was transferred to a special glass sampling tube containing mercury. This sample was then sent to the chemist for analysis. The sample of gas for the Junker calorimeter was also taken from the above sampling device by connecting the burner of the calorimeter through rubber tubing to the nipple. When operating the calorimeter,

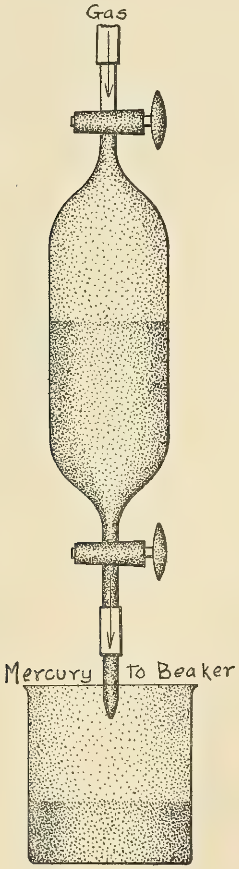

FIG. 6

samples were taken continuously, one after the other.

In order to obtain correct samples of gas, they should be drawn from the main continuously and at a uniform rate of flow. With the aspirator bottles above mentioned, the condition of uniform flow was practically impossible at the time of sampling.

Later, the gases were collected in glass sampling tubes containing mercury. Each tube held about 600 cc. The tubes were connected directly to the nipple leading from the sampler, and the mercury was drawn off through a glass cock located at the bottom of the tube. The mercury passed through the cock and dropped from a glass tube, the opening in the end of which had been made of such size as to allow the mercury to run from the tube in about two hours' time. Fig. 6 illustrates this arrangement. The apparatus has the advantage of collecting the sample over mercury, which eliminates small errors that alwaysresult from the absorption or liberation of gases by the water, and in addition permits the observer to see at a glance whether or not stoppage of the flow of mercury has occurred.

(5) *Determining the Heat Value.*—The heating value of the gas has been determined by the Junker calorimeter and by computation from the analysis of the gas. The latter value is assumed to be more nearly the true value, and has been used in the computations. It is assumed to be more nearly the true value for the reason that the gas samples from which the analyses were made were continuous samples taken over the entire period of the test, while samples for the Junker calorimeter were more or less intermittent, due in the case of some of the earlier tests on the Philadelphia and Reading coal, to poor gas, which would not burn at times, and again, to the necessity of using the operator on other work. There are, also, certain errors such as radiation and conduction and possibly errors in the meter which enter into the calorimeter determinations and for which allowance cannot readily be made. Again, the thermometers used in measuring the temperature of the entering and leaving water read only to tenths of a degree so that an error of 0.5 of one per cent could easily be made in estimating to hundredths, as the rise in temperature of the water was frequently not greater than two or three degrees.

It was found by actual trial that radiation and conduction could easily affect the readings to the extent of two per cent in making determinations upon producer gas. The temperature of the water used in the calorimeter in the case of all tests was below the room temperature, so that the heat was conducted into the calorimeter. This tended to make all determinations about two per cent high. Upon calibrating the gas meter used with the calorimeter, it was found to read a fraction over two per cent low. The error in the meter was, therefore, considered to offset the error due to conduction and radiation.

On account of the above causes, it is believed that the heating value of gases whose principal constituents are simple gases, such as CO and H_2, may be determined with a greater degree of accuracy by computation from the analysis rather than by the calorimeter, especially where the latter is operated under conditions existing on a test and possibly by one unfamiliar with the errors likely to be made in using the instrument.

In the case of all the present tests on which the calorimeter was run continuously, the heating value as determined by the calorimeter checked the heating value as determined from analysis within less than three per cent, and on a number of these within one per cent. This seems to indicate that either method of obtaining the heating value is accurate if proper care is used.

(6) *Error Due to Vapor Pressure of Water.*—An error that caused considerable discrepancy between the heating value as given by the calorimeter and that as given by the analysis, and which resulted in about ten days of investigation upon the accuracy of the Junker calorimeter, was the neglect of the effect of the vapor pressure of water contained in the gas passing through the meter. This source of error had been recognized in the deriving of the formula for the calorimeter that appears in the Appendix, page 83, item 120, and had been allowed for, but in temporarily working up the heating value on some of the tests, this formula was not used, and this error was lost sight of. The result was an error of from two to four per cent, which could not be accounted for after allowing for radiation and other errors in the use of the apparatus. As we have since found that this is an error that is not usually recognized or allowed for by engineers, it will not be out of place to discuss and indicate its magnitude.

The gas entering the Junker meter is saturated with the vapor of water. Consequently this vapor is under the pressure due to the temperature of the gas. According to the laws of Dalton, if a mixture of gases is inclosed within a vessel, the volume of each gas occupies the entire volume of the vessel and each gas is under its own pressure. The sum of the pressures of the constituents of the mixture is equal to the total pressure within the vessel.

The total absolute pressure within the meter is the barometer pressure plus the pressure in inches of water indicated by the U tube attached to the pressure regulating device that accompanies the meter. The temperature of the gas within the meter is obtained from the thermometer. Assume that the total pressure in the meter is 30 inches of mercury absolute, and that the temperature of the gas is 70° F. We find from the steam table that the vapor pressure of the water is .73 in., the total pressure of the mixture is 30 in., consequently, the pressure of the dry gas is $30.0-0.73=29.27$ inches. If the temperature in the meter is 100° F., the pressure of the vapor is 1.94 in., and the pressure of the dry gas is $30.0-1.94=28.06$ in. of mercury.

From these examples, it will be seen that an error of about $\frac{.73}{30} \times 100 = 2.4$ per cent will be made at 70°F. by neglecting the effect of the vapor pressure in computing the standard volume of gas used by the calorimeter and that an error of about $\frac{1.94}{30} \times 100 = 6.5$ per cent at 100° F. will be made. The same error will be made in computing the total volume of gas discharged from the producer, as indicated by the gas meters.

The effect of the above error is to give a low value for the heat of combustion of the gas, and to give a high value for the total volume of gas generated by the producer. If, therefore, no correction is made, the total heat contained in the gas generated by the producer, since it is the product of the two quantities, will not be in error, and the efficiency of the producer will consequently not be in error. If, however, the total volume of gas generated has been corrected for vapor pressure, and the volume of gas used by the calorimeter has not been corrected, which is frequently the case, the efficiency of the producer will be low by the amount of this error.

(7) *Analyzing the Gases.*—The analysis of the gas was made in the Hempel gas analysis apparatus and over water. The burette used was water-jacketed to prevent changes in temperature

affecting the results, while the water used in the burette was saturated with gas.

In some of the later tests, the gases were collected in gas sampling tubes holding about 600 cc. and were collected over mercury. The analysis was also made over mercury. It is believed that this was at least, a safe precaution, as the water in the aspirator bottles previously used for sampling, and in the burette, even if saturated with the gas beforehand, might either absorb or give off small quantities of the gas. There are also other advantages in the use of the "accurate" method which need not be discussed here.

(8) *Measuring the Weight of Air Used.*—As the weight of air is not used in calculations of the first importance, it was not considered necessary to measure this quantity, as it could be computed from the weight of nitrogen appearing in the gas with an accuracy well within 5 per cent. This has been done for all tests and the result appears under item 97 of Table 5.

(9) *Measuring the Temperatures.*—All temperatures with the exception of the temperatures in the fuel bed and the temperature of the gases leaving the producer, were taken with mercury thermometers, all of which had previously been calibrated and calibration curves plotted. All mercury thermometers were used with their bulbs in direct contact with the medium whose temperature was to be measured. In calibrating, the Reichsanstalt standards of the department of Physics were used. In making the computations, the corrections were taken from the calibration curves.

(10) *Temperatures of Gases Leaving Producer.*—The measurement of the temperature of the gases leaving the producer was effected by the use of a platinum-rhodium thermocouple and a Siemens & Halske millivoltmeter calibrated to read direct in degrees Centigrade. This couple and voltmeter were compared with a Reichsanstalt standard, reading in degrees Centigrade and to 500°. After making the proper stem correction for the standard, the readings of the thermocouple practically agreed with the readings of the standard. For higher temperature, the thermocouple readings were taken at the melting point of zinc, 419° C., the melting point of silver, 961° C., and the melting point of copper, 1084 ° C., and were found to be practically correct. In using the platinum-rhodium couples, considerable care had

to be taken in order not to have the couple contaminated with gases, as such contamination would destroy the calibration and ultimately make the couple worthless. As a couple of this type five feet in length costs about $50.00, it is evidently necessary to use some care in this respect. In order to protect the present couple, the hot junction was placed in a quartz glass tube about $\frac{1}{8}$-in. inside and $\frac{1}{4}$-in. outside diameter. This tube was then inserted in a brass thermometer cup which was screwed into the gas main leaving the producer at *O*, Fig. 3. The cold junction of the thermocouple was placed in melting ice.

After a number of tests had been run, it was considered possible for the conduction of the brass thermometer cup to lower the temperature as given by the thermocouple. In order to test this, a mercury thermometer, and later a Hoskins thermocouple, the latter having been compared with the platinum-rhodium couple, were placed in direct contact with the gases. The producer was then run at different capacities, in order to produce different temperatures in the leaving gases, and simultaneous readings of the Hoskins couple exposed to the gases and of the platinum-rhodium couple protected by the thermometer cup and quartz glass tube, were taken. The curve of Fig. 7 was plotted from the data taken on this experiment. The results were somewhat startling.

As the points fell on practically a straight line, there could be no doubt of the effect of the thermometer cup and the quartz glass tube upon the reading of the thermocouple. The temperatures used in the computations were taken in degrees F. from curve 1 of Fig. 7. The actual readings of the platinum-rhodium couple in degrees Centigrade were plotted as abscissas while the corrected readings in degrees F. were plotted as ordinates. Curve 2 of Fig. 7 is a curve showing the relation between degrees Centigrade and degrees Fahrenheit, and was used in transferring temperature from one scale to the other. The corrected average temperature of the gases leaving the producer, in degrees F., is given in Table 5, item 39.

(11) *Temperatures in the Fuel Bed.*—The temperatures in the fuel bed were obtained on several tests by the use of a platinum-rhodium thermocouple and the Siemens and Halske galvanometer. The hot junction of this couple was placed in a $\frac{1}{4}$-in-

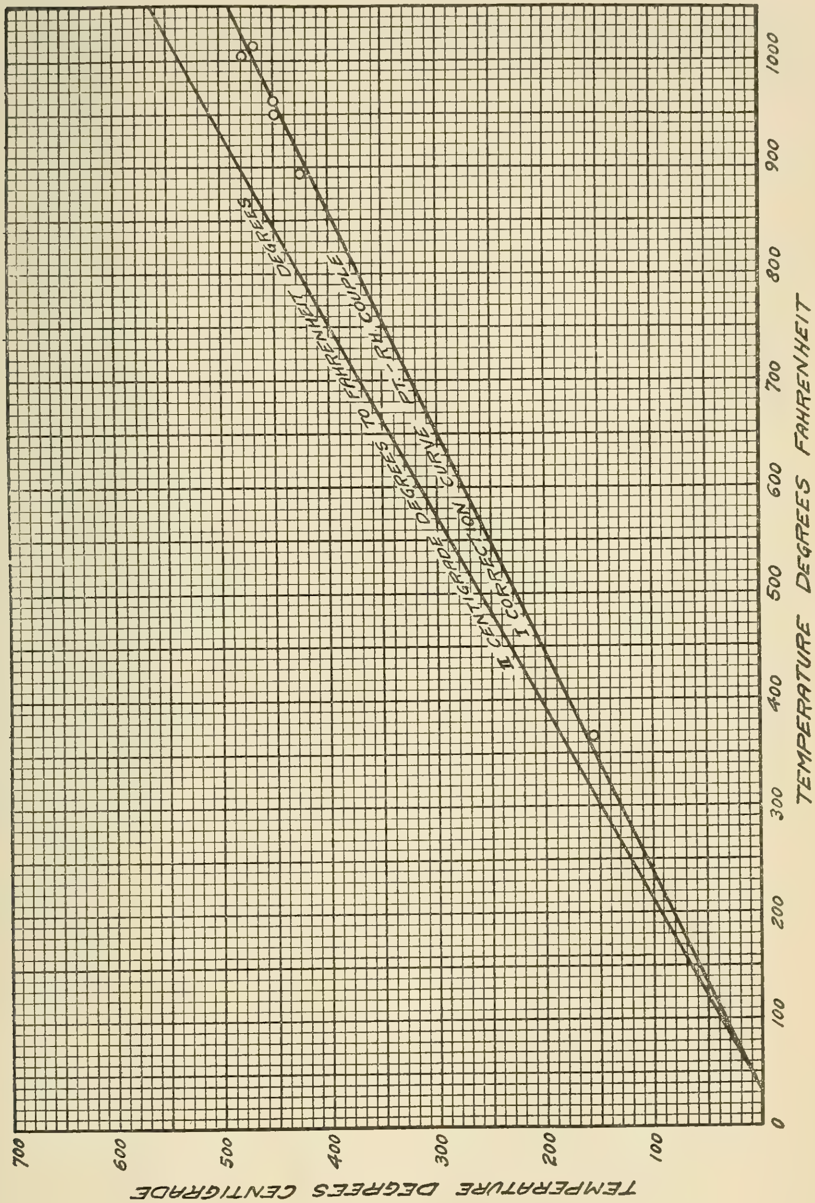
II CENTIGRADE DEGREES TO FAHRENHEIT DEGREES
I CORRECTION CURVE PT.-RH. COUPLE
TEMPERATURE DEGREES FAHRENHEIT
0
100
200
300
400
500
600
700
800
900
1000
TEMPERATURE DEGREES CENTIGRADE
100
200
300
400
500
600
700

FIG. 7

quartz glass tube about 30 in. long, the quartz tube in turn being placed in a $\frac{3}{8}$-in. iron pipe closed and pointed at one end. The pipe containing the hot junction of the thermocouple was then

TABLE 3

Temperature Through Fuel Bed

Test No.	Time	Zone No.*	Temperatures °F.		
			3 inches from near Side of Lining	At Center	3 inches from far Side of Lining
6	6:40 to 6:50	1	1652	1535	1688
		2	2192	1742	....
		3	....	1782	1922
		4	1832	2282	1048
8	1:52 to 2:20	1	2490	2120	2060
		2	1832	2247	2327
		3	....	2282	1975
		4	....	1724	1922
18	11:30 to 12:40	1			2300†
		2	2350	2163	2250
		3	....	2380	2375
19	11:00 to 11:40	1	2000	1970	1950
		2	2300	2160	2300†
		3	2350	2137	2250
21	11:45 to 12:30	1	700	575	375
		2	1560	1550	1475
		3	2075	1875	1725
25	10:05 to 10:55	1	2100	2037	2025
		2	2350	2225	2275
		3	....	2200	2400
27	10:30 to 11:40	1	1075	1075	1650
		2	1580	2000	2000
23	8:43 to 9:35	1	1237	1610	1625
		2	1500	1812	1900
		3	1600	2037	2225
	3:50	1	1950	1675	1700

*Zone No. 1 = 24 in. above grate.
Zone No. 2 = 18 in. above grate.
Zone No. 3 = 10 in. above grate.
Zone No. 4 = 3 in. above grate.
† indicates that the temperature rose above the softening point of the thermocouple and hence was not obtained.

inserted in holes drilled through the walls of the producer. These were drilled one above the other at 3 in., 10 in., 18 in. and 24 in., respectively, from the grate. Temperatures were taken first through the upper hole, at 3 in. from the near side, at the center and 3 in. from the far side, and in the same positions through each of the other holes.

The platinum-rhodium couple did not prove entirely satisfactory for this work, on account of the difficulty in properly protecting it. When the end of the iron pipe entered a zone where clinker was forming and where there were large holes in the fuel bed through which the air was passing, the temperature rose rapidly and either melted off the end of the pipe or bent it so that it was difficult to remove. After losing several inches from the end of the couple and at the same time contaminating it with the gases from the fuel bed, it was decided to try the Hoskins couples. These are a patented thermocouple of considerable mechanical strength, supposed to be unaffected by furnace gases. The composition of the elements forming the couple is not known. The temperature as indicated by the Hoskins couple is read in degrees Fahrenheit direct from the galvanometer provided. This latter reads to 2500° F. It was found, however, that the couples softened at 2250° F., so that it was not possible to go higher than this. These couples are much heavier than the platinum-rhodium couples, and, according to the manufacturers' statement, could be used in the fuel bed without protection. It was found better, however, to enclose them in iron pipes. The temperature n the fuel bed was taken by means of the Hoskins couple from test 18 to test 31. The temperature so observed will be found in Table 3.

(12) *Measuring the Water Used.*—The water fed to the producer from the vaporizer in tests 2 to 8 inclusive and in tests 31, 32 and 38, was obtained by weighing a tank filled with water which rested on platform scales. This tank was placed on the charging platform above the producer. The water was allowed to drip from the tank into the vaporizer. A constant level was maintained on the vaporizer by allowing the water to overflow into a second tank resting also on platform scales. The weight of water fed to the producer was therefore the difference between the weight of the supply tank and the weight of the overflow tank.

In all other tests the vaporizer was blanked off and a steam jet supplied the moisture necessary in the operation of the producer. The jet passed through a small thin plate orifice. The pressure on the orifice in pounds per square inch was taken, and after the test, the orifice was calibrated under the pressure observed on the test. The jet was located beneath the grate and in the center of the ashpit. Any steam condensing in the ashpit from the jet overflowed, and was collected and weighed at the end of the test. The weight of this overflow was small and in a number of tests there was no overflow. The weight of water supplied to the producer was obtained from the pressure on the orifice and the calibration at this pressure. The actual weight that entered the fuel from the steam jet was the difference between the above weight and the weight of the overflow. The former quantity is given under item 79A of Table 5. Besides the water from the vaporizer, there is also the moisture carried in by air and by the coal. These weights are given under items 79B and 79C respectively. The computations for the weight of moisture carried in by the air are given in the Appendix, page 87, items 104 and 105.

The water supplied to the first scrubber was measured by a water meter, which was calibrated before the test. The water used by the second scrubber was not considered, as this was only incidental to the method of testing.

(13) *Weight of Moisture in the Gas.*—The weight of moisture in the gas leaving the producer was determined by two separate methods. First, by drawing a sample of gas through a calcium chloride tube, by means of a water aspirator. A small wet gas meter was placed between the calcium chloride tube and the aspirator from which the volume of gas was determined. The moisture accumulating in the tube was weighed. From the data obtained from this apparatus, the per cent of moisture in the gas leaving the producer was determined. In the second method, the weight of water decomposed in the fuel bed was computed from the analysis of the gases, Appendix, page 87, item 86. This weight is given in Table 5, item 80. The total weight of moisture entering the producer is given under item 79; the difference between the two items gives the weight of water in the producer gas. It is believed that the percentage of moisture in the gas based on this determination is the more accurate.

(14) *Ash and Refuse.*—The ash and refuse taken from the grate during the test, together with that resulting from the cleaning at the end of the test, were collected and weighed. The whole was then quartered and sampled, and the sample sent to the chemist for analysis. The weight of carbon lost through the grate was determined from the total weight of ash and refuse and the per cent of carbon as given in the chemist's report. It will be noted from item 49 of Table 5 that in several of the tests, the percentage of ash and refuse obtained is lower than the percentage of ash in the coal as given by the chemist's report, item 53. This is due to the impossibility of removing all of the ash from the fuel bed at the close of the test. This ash may have been either in the form of clinker which accumulated on the lining of the producer, or in the form of a soft white powder which packed into the interstices around the coal. The failure to obtain the correct or true weight of ash formed during the test, as explained under the measurement of the weight of coal fired, is not of great importance, as the weight of ash and refuse is used only for the determination of the weight of carbon lost through the grate.

In a number of tests, ultimate analyses were made on the ash and refuse for the purpose of investigating the formation of clinker. These analyses are given under item 63 of Table 5. The percentages are based on the weight of "earthy matter."

(15) *Soot and Tar.*—The amount of soot and tar escaping the scrubber of the hard coal producer is, under normal conditions, very small, and as a rule very little trouble results from their presence. No attempt was made in the tests to determine their weight. After about 600 hours' operation and the generation of about 2 000 000 cu. ft. of gas, the horizontal pipe leading from the wet scrubber to the steam ejector was taken down and examined. It was found to contain a coating of tar and soot less than $\frac{1}{32}$ in. thick on the inner wall. As this period of time would correspond to about two months, running at 12 hours per day, it may be assumed that the scrubber capacity is sufficient.

(16) *Stand-by Losses.*—Small producers of the present type are usually designed for intermittent operation and are not well adapted for continuous runs of longer than twelve hours' duration. This is a disadvantage due to the size of the producer, and results from the inability to thoroughly clean the ash from the fuel bed

without lowering the heating value of the gas to such an extent as to interfere with the operation of the engine. In larger producers the volume of gas generated per unit of time is large: the fuel bed is also large, so that the air admitted in poking and cleaning the fire represents a very small percentage of the gas volume generated. Also, the proportion of the fuel bed disturbed at one time is relatively small compared with the total area of the fuel bed. On account of these conditions, the fuel bed of a large producer may be cleaned and poked without seriously affecting the quality of the gas, so that continuous operation is a comparatively easy matter, while with a smaller producer of the same type continuous operation would be impossible.

The specifications accompanying the present producer state that it is to be used for runs of not greater than 12 hours. Consequently, there will be a stand-by of twelve hours' duration if the engine is being operated twelve hours per day. As this is the condition that maintains in commercial work, it is of importance that the losses due to this stand-by be known.

In order to determine these, a stand-by test of 120 hours starting October 11, 1909 at 10:20 a. m. and running until October 16, at 10:20 a. m. was made. The test was started by running the producer until a normal fuel bed was obtained, and then cleaning the fires and filling the producer with coal. The producer was then closed down, and at the end of twelve hours, the fires were cleaned, and the producer operated until the gas would burn at the try cock. The producer was again closed down for twelve hours, and at the end of the period, the fires were again cleaned and the above cycle of operations repeated. During the 120-hr. run, the fires were cleaned and the gas producer operated until a working gas was obtained ten times, that is, once every twelve hours.

At the close of the test, 280 lb. of coal were required to fill the producer. This represents a stand-by loss of 28 lb. of dry coal per twelve hours. If we consider that 500 lb. of coal per 12-hr. run is about the normal capacity of the producer, the stand-by loss represents about 5.5 per cent of the dry coal fired or about 6 per cent of the combustible. The results of the stand-by test are given in Table 4.

The stand-by loss is divided into four parts; (1) that which is lost through the grate due to cleaning the fire; (2) that which is lost through the poor gas generated from the time the blower is started until the gas is sufficiently rich for use in the engine; (3) that which is lost in the small quantity of gas generated during the actual stand-by period; and (4) that which is due to the conduction and radiation of heat from the producer during this stand-by period.

The loss through the grate may be obtained from the data of Table 4. It was not deemed sufficiently important to separate the second and third losses, and it was not possible to obtain the fourth other than approximately.

TABLE 4

Results of Test for the Determination of Stand-by Losses.
Time of start, 10:20 a. m., October 11, 1909.
Time of stop, 10:20 a. m., October 16, 1909.
Duration of the trial, 120 hours.
Producer started 10 times.
Fuel used, anthracite.
Commercial name, Scranton pea.

FUEL

1	Size and condition		Pea clean
2	Weight of coal as fired, lb		288.0
3	Percentage of moisture in coal		2.92
4	Total weight of dry coal fired, lb		280.0
5	Total ash and refuse, lb		51.0
6	Quality of ash and refuse		
7	Total weight of combustible, lb		212.0
8	Percentage of ash and refuse in dry coal, per cent		18.2
	ULTIMATE ANALYSIS OF DRY COAL		
9	Carbon (O)	per cent	79.83
10	Hydrogen (H_2)	"	2.59
11	Oxygen (O_2)	"	2.20
12	Nitrogen (N)	"	.82
13	Sulphur (S)	"	1,39
14	Ash	"	13.17
15	Moisture in sample of coal as received	"	2.92
	ANALYSIS OF DRY ASH AND REFUSE		
16	Carbon, per cent		43.00
17	Earthy matter, per cent		57.00
	FUEL PER HOUR		
18	Dry coal fired per hour, lb		2.34
19	Combustible consumed per hour, lb		1.77
20	Dry coal per sq. ft. of grate area per hour, lb		1.40
21	Combustible per sq ft. of grate area per hour, lb		1.06
22	Dry coal per sq. ft. of fuel bed per hour, lb		1.25
23	Combustible per sq. ft. of fuel bed per hour, lb		.94

10. *Duration of the Tests.*—Owing to the conditions under which the tests were run, it was not possible to make runs of longer than

twelve hours' duration. Fortunately, however, it will be found, from the discussion under the measurement of the weight of coal fired, that with the exception of the very low capacity tests, runs of this length were sufficient to reduce the probable error in determining the weight of coal fired, to about two or three per cent. It has also been noted that owing to the small size of the producer, tests of longer duration are hardly practicable. This is due to the fact that toward the end of all 12-hr. tests, the accumulation of ash in the fuel bed necessitated such thorough cleaning as to seriously interfere with the uniformity of the heating value of the gas. As the producer is provided with a plain bar grate and all the cleaning must be accomplished by opening the ash doors, this particular type of producer, while operating with a fair degree of satisfaction on runs of not greater than 12 or 15 hours' duration, would not be satisfactory for continuous runs of longer duration. This has been recognized by the builders and was so stated in their specifications.

As the object of these tests was to show the actual operating efficiency of the producer, and as under these conditions the producer would not be run for greater than 12 continuous hours, the present tests have been made to conform to those conditions as nearly as possible. The producer necessarily shows a lower efficiency under these conditions than it would under continuous operations. The reason for this lower efficiency is the stand-by losses. These are composed of four separate losses, as has been pointed out. One of these affects directly the results of the tests. This is the loss due to the radiation and conduction of heat from the fuel bed and producer during the stand-by period. It results from the fact that at the close of a run or test of 12 hours' duration, the fires are cleaned, and in cleaning, a large quantity of incandescent ash and carbon is removed from the fuel bed; this mass is replaced by the green fuel from above so that after cleaning, the temperature of the fuel bed is low and remains so until the starting of the new run or test. The producer lining, shell water jacket and water also lose heat during this stand-by period. On again starting the producer at the beginning of a test, the fire is blown until a gas sufficiently rich for operation is produced, and the test is then started. The average temperature of the fuel bed and producer has not reached the temperature of normal operation. At the close of the test, this temperature has been reached, consequently, a large quantity of heat must be used in raising the average temperature of the producer at the begining of the test to the average temperature at the close of the test. In the case of the present test, the producer was not in operation continuously and it was not always possible to bank the fires from one test to another, for this reason. The fire in the producer was usually started on an average of about two hours before the test began. Gas sufficiently rich for operating could be obtained in about thirty minutes from the time of starting the fires, the additional time permitting the producer to warm up. Notwithstanding this, however, the difference between the average temperature of the producer at the close and the average temperature on the starting of the test may have been anywhere from 200 to 700°F. The magnitude of this loss and the extent to which it probably affected the heat balance of tests may be best illustrated by an example. Assume that the average temperature of the producer at the starting of the test is 1000°F., assume that the average temperature at the close of the test is 1600°F. The difference in temperature is about 600° F. The

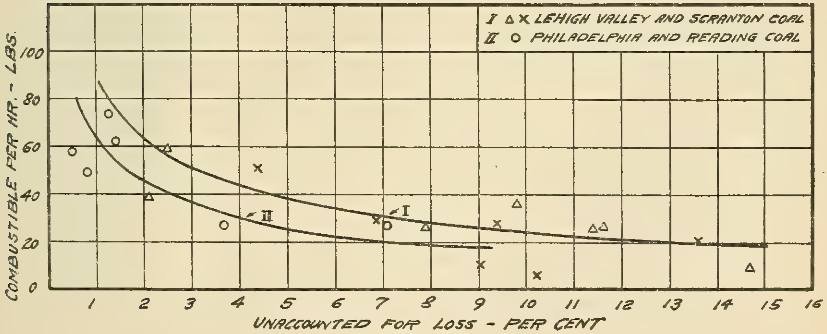

FIG. 8

total mass in the present case represents about 1200 lb. If we assume the specific heat to be .25, the total heat that has been lost during a run in bringing the average temperature of the producer at the start of the test to the average temperature at the close of the test is 1200 × 600 × $\frac{1}{4}$ = 180 000 B. t. u. On the high capacity tests this loss is a very small percentage of the total heating value of the fuel, on the lower capacity tests it is a very large percentage. Suppose 150 lb. of coal are fired on one of the light load tests. The heating value of this coal is 12 500 B. t. u. per lb. The total heat supplied to the producer is 12 500 × 150 = 1 870 000. The per cent loss due to the above is, therefore, $\frac{180\,000}{1\,870\,000}$ = 9.6 per cent. As this loss is largely inherent in the operation of the producer, it was deemed advisable to indicate its magnitude and not eliminate it from the results of the tests.

The curves of Fig. 8 have been plotted from the results of all tests and show approximately how this loss varies with the weight of combustible gasified. These curves would also seem to indicate that the radiation and conduction losses from the producer are between 0.7 and 1 per cent, since the curves become parallel to the Y axis in this neighborhood.

11. *Forms for Computation and Discussion of Items of Table* 5.—Three forms have been drawn up for use in making the computations for the tests. Table 5 is made according to form 1, which is used for the presentation of the results of the test; a blank of this form is shown in the Appendix. Form 2 was made to include all items involved in computation of the results and form 3 contains the derivation and discussion of the formulas used. In working up the tests, the average total quantities are taken from the original log sheets, corrected and placed on form 2. The item number of form 3 refers to the item number of this form. The results are computed in the order of form 3 and placed on form 2, from which the results compiled are placed on form 1. In order to find the formulas used in computing any result given in Table 5, this result must be found on form 2, and the item number corresponding to this result on form 2 corresponds to the item number of form 3 under which the formulas used will be found. For example, suppose that it is desired to find the formulas used in computing the cold gas efficiency as given in Table 5. Referring to form 2, Appendix, it will be found that the cold gas efficiency on this form appears under item 155. By referring now to item 155 of form 3, the formulas required will be found.

One of the important considerations in developing the forms has been to include such items as will give proof of the accuracy of the work, and that will point out the nature of any serious errors that are always likely to creep into experimental work.

The gas volume has been determined from a previously calibrated meter. This volume has been checked in most tests by computing the volume of gas from the weight of coal consumed, the analysis of the coal and the analysis of the gases. If the volume of gas as given by the meter is not more than 5 per cent lower than the computed volume, it is assumed that the gas volume as determined by the meter is correct. If there is a greater variation than this, the error may be either in the weighing or estimation of the coal, in the meter, or in the analysis and sampling of the gas. If the heating value of the gas as computed from the analysis checks the heating value as given by the Junker calorimeter, the conclusion is that the error is on the side of the coal. If the volumes check, and also the heating value of the gas as determined from the analysis and from the calorimeter, the conclusions are that the only serious error that can exist must be in the measurement of the temperature of the gases leaving the producer. Even this temperature may be checked by computing from the weight of scrubber water, item 90, and from the rise in temperature of the scrubber water, the heat lost to this by the gases leaving the producer.

The word combustible has been used in these tests according to the definition appearing in the Appendix, forms 2 and 3, item 54. As this word has been used in an arbitrary sense by a number of writers and also by the engineering societies, its definition is of considerable importance.

The calorific value of the gas is given under items 104 to 105 Table 5 and form 1. The high value is defined as the total heat given out by a cubic foot of gas at 62° and 30 in. of mercury when it is burned in oxygen and the products resulting from combustion are brought back to 62° F. The net or effective value is equal to the "high" value minus the latent heat contained in the water that is formed by the combustion of the hydrogen. It will be seen that if the gas is used under such conditions that it is exhausted at a temperature greater than 212° F., this latent heat is of no use in the cycle of operation. This is the case where the gases are used either in the gas engine or for firing boilers. The low or effective value is given under item 104a which is computed from the analyses of the gases.

Under item 126 is given *the grate efficiency.* This is a very variable quantity and depends upon the fireman, the size of coal fired, the amount of ash contained in the coal and upon the number of times the fires require poking and cleaning. With large producers and careful firing, this item should not be less than 95 per cent. With small producers of the type used in this work 95 per cent is an excellent result. With the coals used on the tests, from 80 to 90 per cent is probably a fair value for this item.

The hot gas efficiency based on the high heating value of the gas is given under item 127. This value varies from 100 per cent principally by the percentage of the radiation, conduction and unaccounted-for loss and by the percentage of the heating value of the fuel lost through the grate. The hot gas efficiency is of no special importance where the gases are used for power purposes.

The cold gas efficiency based on the high heating value of the gas appears under item 128, again under item 128a, based on the low or effective heating value of the gas. This efficiency for both high and effective heating values has also been based on 100 per cent grate efficiency or upon combustible and is given in items 128c and 128d. This latter value has been computed in order to show certain relations that are independent of the grate efficiency.

12. Under *unaccounted-for loss* may be grouped the following losses.

a. Radiation
b. Conduction
c. Loss due to tar and soot and to the absorption of the gases by the scrubber water.
d. Loss due to difference in temperature between the initial and final conditions of the fuel bed.
e. Minor losses which may be either positive or negative such as the loss due to the sensible heat in the fuel and in the ash.
f. Experimental errors made on the tests.

PART III. RESULTS OF THE TESTS

13. *General Discussion of the Tests.*

(1) *Tests with Philadelphia and Reading Anthracite.*—Tests 2 to 8 inclusive, Table 5, were run on Philadelphia and Reading anthracite coal, chestnut size. This was in appearance a dirty anthracite, probably 50 per cent of which would pass over a $\frac{3}{4}$-in. mesh and through a $1\frac{1}{2}$-in. mesh screen, while 25 per cent would pass a $\frac{5}{16}$-in. mesh.

The average percentage of ash as taken from the analysis of he dry coal was approximately 15 per cent. Analysis of this ash given in Table 5, under test 4, shows that 90 per cent by weight was composed of the oxides of silicon, iron, and aluminum; the remaining 10 per cent consists of the oxides of calcium and magnesium, which in combination with the above, are sufficient to form a semi-fusible, viscous ash at the temperature obtaining in the fuel bed of the gas producer.

On the tests it was found that the clinker began to form at very low temperatures, and by the time the temperature of the fuel bed rose to an efficient working temperature, the formation of clinker on the lining of the producer was so rapid as to interfere with the quality of the gas. By the use of larger quantities of steam, or at lower capacities, it would doubtless be possible to use this coal in a producer of larger size with satisfactory results. With a producer of the size and type used on the tests, satisfactory peration is practically impossible.

This series of tests is of little value except to illustrate the ect of a fuel containing a fusible ash upon the operation of a mall producer. Owing to the formation of clinker on the sides f the producer, the fuel bed is greatly reduced in area, and there i the tendency for the formation of holes which permit the air to rush through, resulting in high temperature and poor gas. Owing to the frequency of poking, large quantities of incandescent coal drop into the ashpit, thus reducing the grate efficiency. Fig. 9 is a graphical log of test 6.

(2) *Tests with Lehigh Valley Anthracite.*—Tests 15 to 21 inclusive were run on Lehigh Valley anthracite, chestnut size. This was extra large chestnut and clean in appearance. Ninety per cent of this coal would pass through a 2-in. mesh, while all of it would practically pass over a $1\frac{1}{4}$-in. mesh. The average percent-

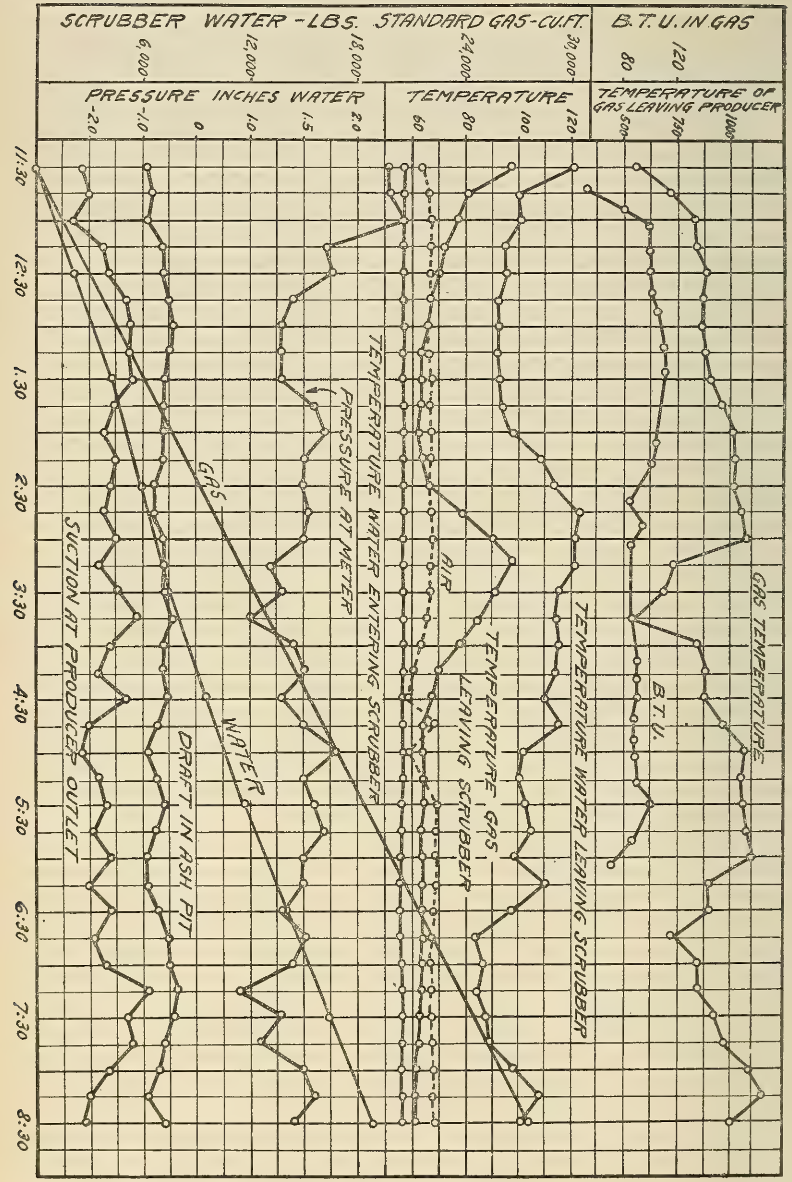

FIG. 9
GRAPHICAL LOG TEST NO. 6

age of ash as taken from the analysis was approximately 15 per cent.

The ash taken from the producer at the close of the tests was soft and white and contained small pieces of clinker. There was practically no tendency for the formation of large clinker arching across the fuel bed at the higher temperature.

The conditions that maintained in this series were fairly uniform, considering the size of the producer. Fig. 10 and 11 show the graphical logs for tests 17 and 20, respectively.

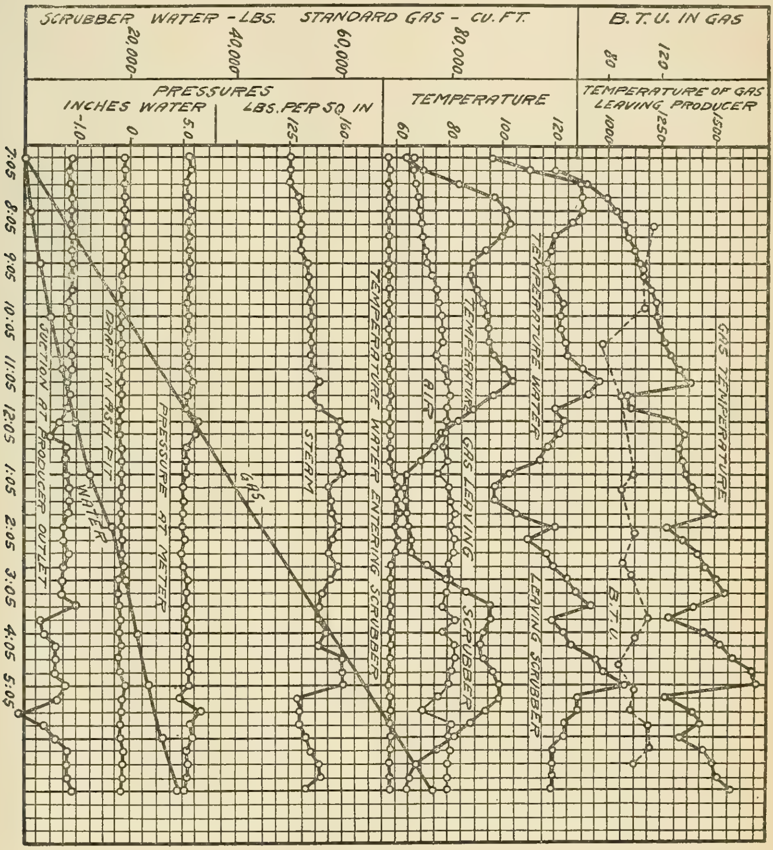

FIG. 10
GRAPHICAL LOG TEST NO. 17

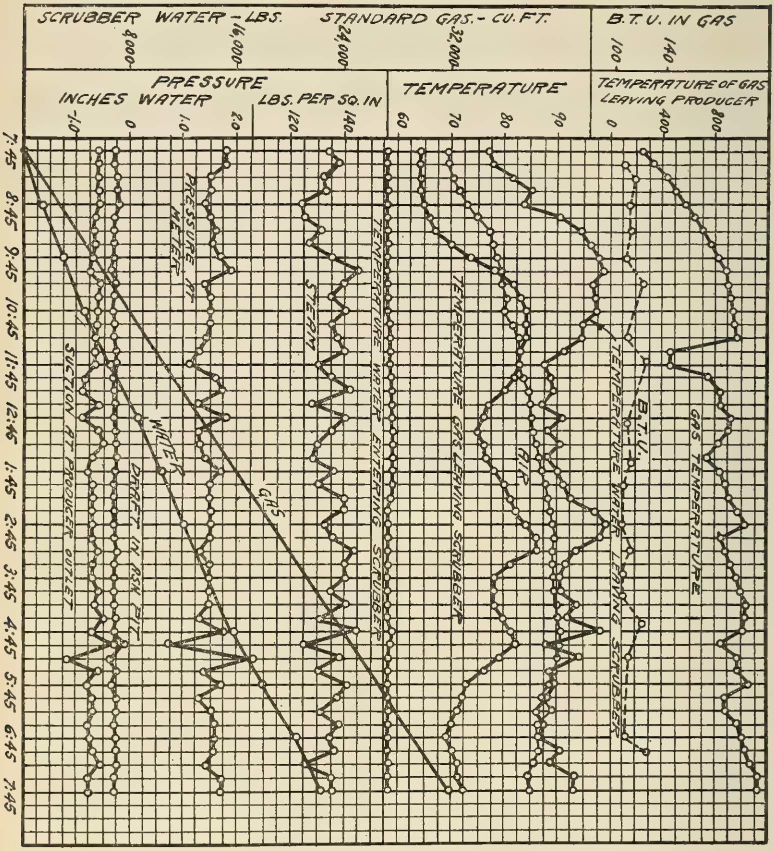

FIG. 11
GRAPHICAL LOG TEST NO. 20

The average heating value of the gas for all of the tests was 110. The variation of the heating value on all of the tests, while probably sufficient to cause considerable trouble in the operation of an engine driving electric lighting machinery, would not interfere seriously with the operation of an engine where close regulation was not a prime consideration.

(3) *Tests with Scranton Pea Coal.*—Tests 23 to 27, including tests 31, 32 and 38 were run on Scranton pea anthracite. This coal was clean in appearance and like the other two coals, contained on an average about 15 per cent ash, while the calorific value corresponded to the calorific value of the other coals and

was about 12 800 B. t. u. per lb. of dry coal. It would all pass over a ⅜-in. mesh and through a ¾-in. mesh. Analysis of the ash is given under test 23. This shows it to be an ash consisting of about 96 per cent of the oxides of silicon, iron and aluminum, while the remainder is made up of the oxides of calcium and magnesium, which are present in insufficient quantities to make the ash readily fusible at the temperature maintaining in the fuel bed.

The ash as taken from the fuel bed was soft and fine, mixed with small pieces of clinker. There was very little tendency toward arching and the tests were the most satisfactory of the series. The conditions were as uniform as could be expected,

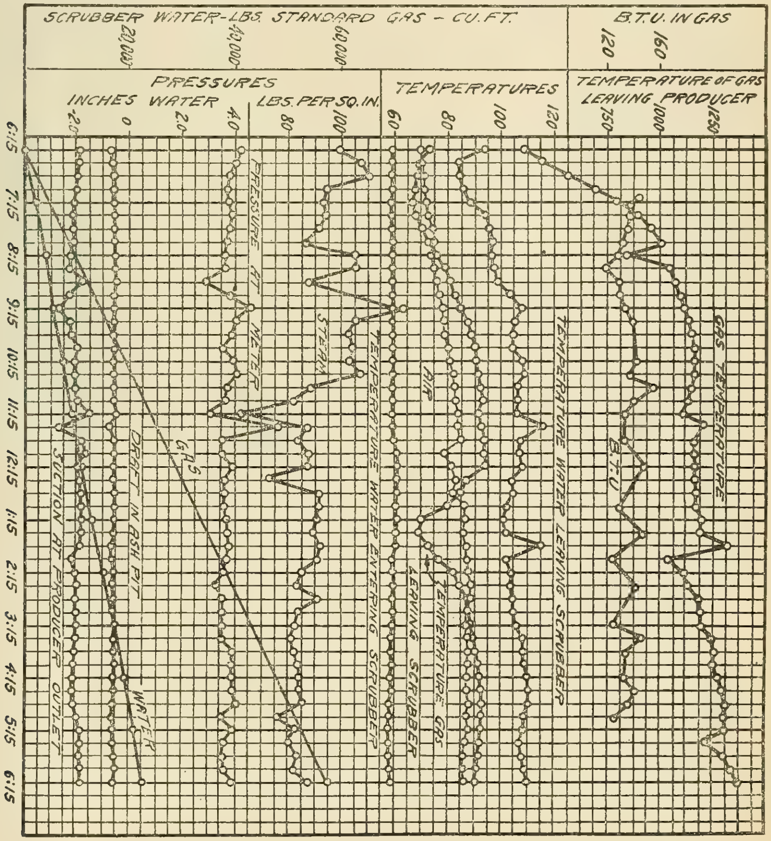

Fig. 12
Graphical Log Test No. 25

and the efficiency reasonably high. Fig. 12, 13, and 14 are graphical logs from the tests of this coal.

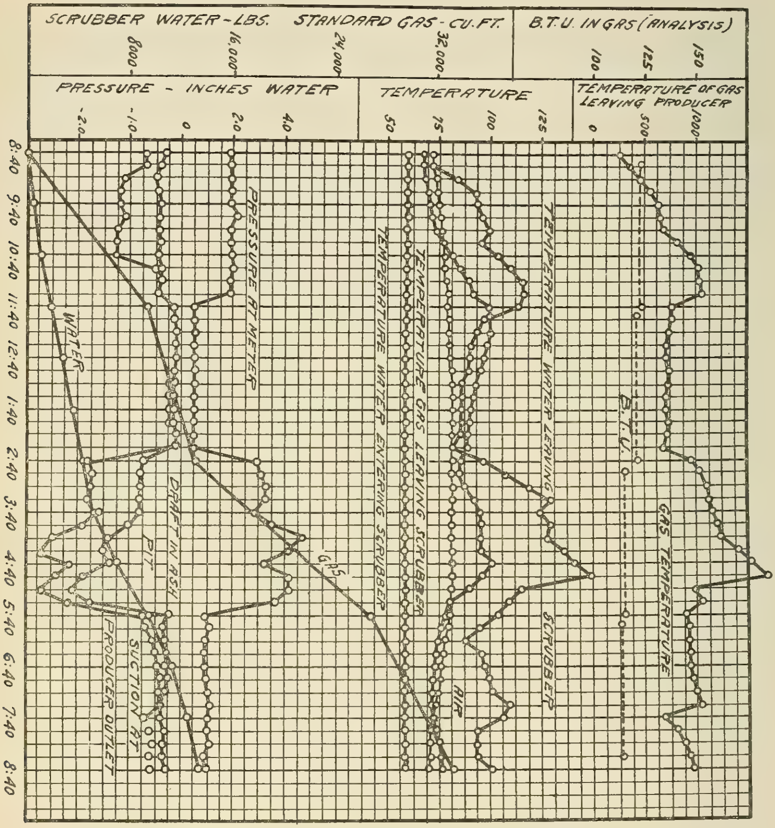

FIG. 13
GRAPHICAL LOG TEST NO. 31

Fig. 13 shows the results of test 31, which was a variable load test run for the purpose of showing the effect of suddenly varying the rate of gasification. For the first three hours of the test, the producer was operated at the rate of about 3300 cu. ft. of gas per hour; for the next three hours at the rate of 1155 cu. ft.; for the third 3-hr. period at 4500 cu. ft.; and for the last 3-hr. period at a rate about 2200 cu. ft.

(4) *Tests with Gas House Coke.*—Tests 28, 29, and 30 were run on

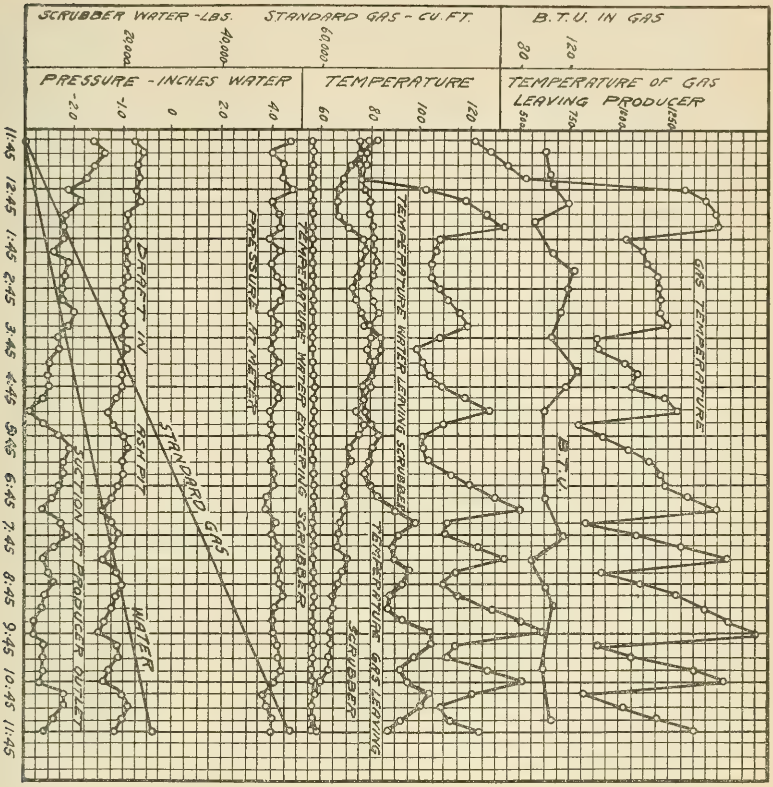

Fig. 14
Graphical Log Test No. 32

gas house coke containing about 14 per cent ash. The appearance was dirty and the size very irregular. Thirty per cent of this would doubtless pass a $\frac{5}{16}$-in. mesh, 50 per cent a 2-in. mesh, while the remainder would pass a 4-in. mesh.

There was some trouble due to the formation of clinker, and considerable trouble caused by a tendency of the coke to pack in the hopper, thus preventing its descent into the fuel bed. In spite of this, the conditions that maintained on the tests were fairly uniform, and it is believed that very little difficulty would be experienced in using a coke of uniform size and quality in this type of producer. Fig. 15 is a graphical log plotted from the results of test 30.

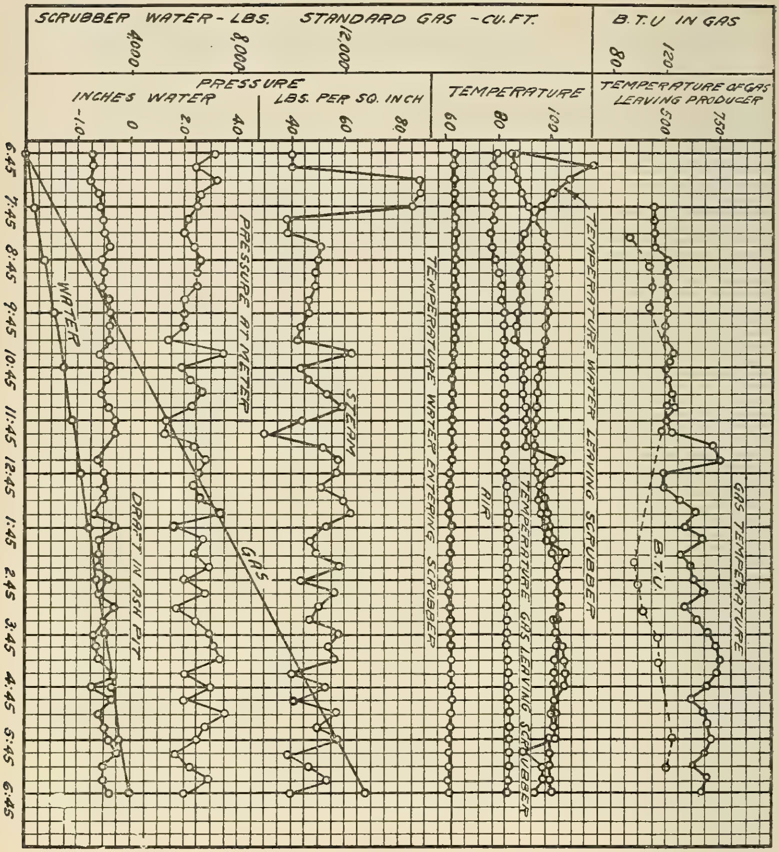

FIG. 15
GRAPHICAL LOG TEST NO. 30

(5.) *Test No. 14.*—Test 14 was a special test run on the Philadelphia and Reading coal to determine if the ash in this coal could not be made sufficiently fusible to run from the fuel bed. This test will be discussed under the formation of clinker.

14. *Percentage of CO_2.*—The percentage of CO_2 in the gas is ordinarily considered to be a measure of the efficiency of a producer, low percentages indicating high efficiency while high percentages indicate the reverse in efficiency. This is to a certain extent true in most producer practice, but it is not necessarily so, as the following will illustrate. If the heat resulting from the formation of CO_2 is utilized in the decomposition of the vapor of water for

the production of H_2, which enriches the gas, then no appreciable loss results. If, however, the CO_2 results through poor operating methods, such as insufficient or improper poking, resulting in holes in the fuel bed and thus permitting the air to rush through, then the presence of a high percentage of CO_2 is indicative of a low efficiency, and this condition will manifest itself in excessively high temperatures of the leaving gases.

This latter condition is illustrated by the results of all the tests on the Philadelphia and Reading coal (see Table 5). The temperatures of the gases leaving the producer, item 39, are excessive, the CO_2 item 117, is high, while the efficiencies, items 126-128d, are low.

The former condition, in which both the CO_2 and the efficiency are high, is illustrated by the tests on the Lehigh and Scranton coals. The principal results of test 23, which have been placed in Table 6 for convenience in discussing, illustrate this condition. The per cent of CO_2 in the gas in this test averaged 10.15. The temperature was, however, low, 800°F., and the efficiency high, thus showing that the fuel bed was in good condition but at so low a temperature, due to the use of a large amount of steam in the air fed to the producer, as to produce a predominance of the reaction 3 which has been discussed in page 6 of the theory. Test 24, also placed in Table 6, shows practically the same efficiency but with 4.04 % CO_2 in the gas. This is due to a high temperature in the fuel bed which tends to cause reaction 4 to predominate, resulting in a high percentage of CO, practically the same temperature of the leaving gases as was obtained in test 23, and practically the same efficiency.

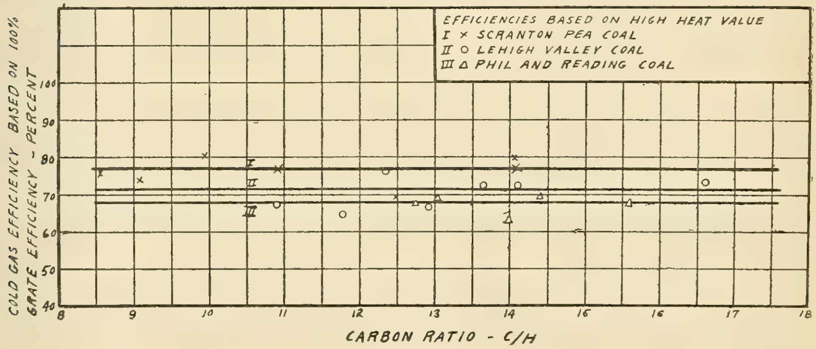

FIG. 16

The curves of Fig. 16, 17, 18, and 19 also show that the per cent of CO_2 has very little effect upon the efficiency of the producer. The theoretical efficiency curve showing the efficiency for different percentages of CO_2 on the assumption that the heat liberated through the formation of the CO_2 is lost in sensible heat, has been drawn and is shown in Fig. 19. The difference between the actual curves and the theoretical curve is a measure of the amount of heat conserved through the decomposition of water vapor.

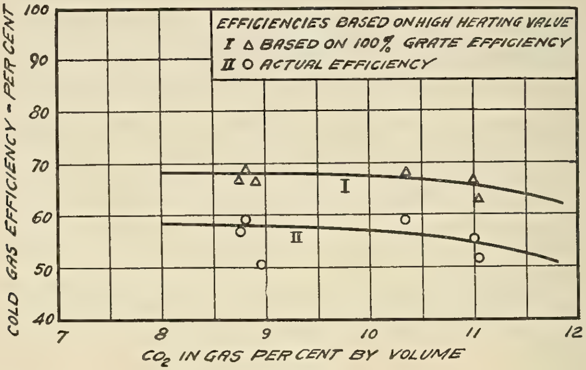

FIG. 17

CO_2—EFFICIENCY CURVES FOR PHILA. AND READING COAL

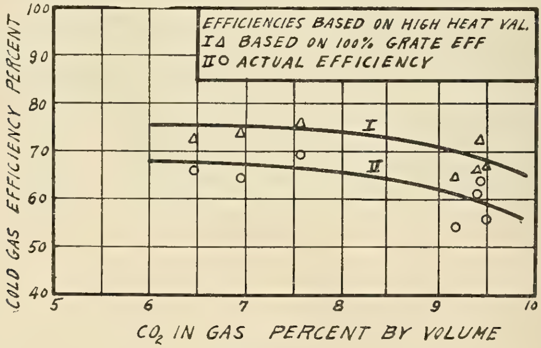

FIG. 18

CO_2—EFFICIENCY CURVES FOR LEHIGH VALLEY COAL

The efficiency curves on this figure have been affected by the unaccounted-for loss which has been discussed on page 37, and has resulted in lowering the points in the low capacity tests to such an extent as to make these curves concave to the axis.

The curves of Fig. 18 are also affected by the unaccounted for loss, but in this case the gas from the low capacity tests ran high in CO_2, owing to the use of a large quantity of steam, which resulted in causing the curves to drop off at the high percentage of CO_2 faster than they otherwise would.

The curves of Fig. 16, showing the relation between the efficiency and the carbon ratio, or the ratio of the weight of carbon to the weight of hydrogen in the producer gas, illustrate the point under discussion, showing that the efficiency of the producer is practically independent of the amount of hydrogen in the gas, consequently, of the per cent of CO_2 in the gas. Fig. 20 shows how the per cent of CO_2 in the gas depends upon the weight of water decomposed per pound of combustible.

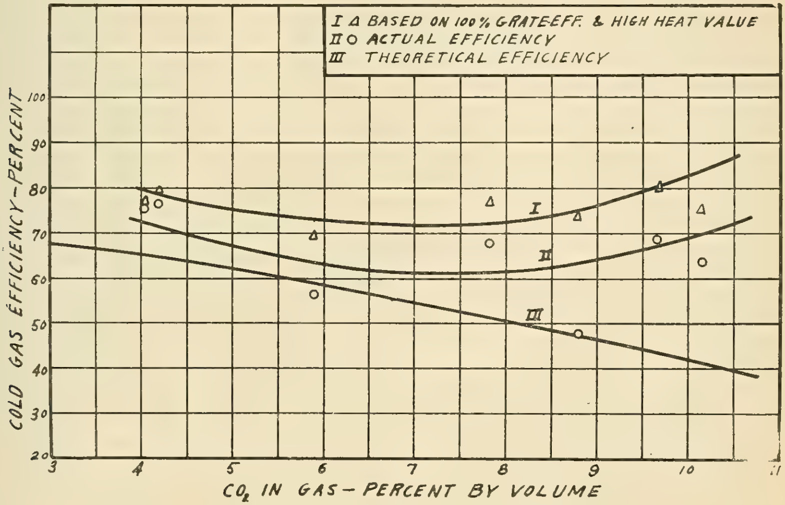

FIG. 19

CO_2—EFFICIENCY CURVES FOR SCRANTON PEA COAL

15. *The Effect of the Size of the Fuel.*—The determination of the effect of the size of the fuel upon the composition of producer gas and also upon the efficiency of the product is complicated by the difference in operating conditions that may not be recognized and upon the difference in the surface effect of the incandescent fuel upon, first, the reactions of oxygen and hydrogen and later on the reaction of CO_2 on this fuel. The exact nature of the surface

effect, which is called "catalytic action", and under which a number of different effects are grouped, is very little understood at the present time. It probably results from chemical reaction on the surface of solids in contact with gases, which depend upon the state or form of the solid, such as charcoal, lampblack, coke or anthracite coal, and in the case of these fuels upon any impurities contained in them. The result of catalysis is to hasten any reaction that may be taking place between the solids and the gases in contact with them, or between the gases themselves. It is believed, however, that the ultimate extent or that the equilibrium of the reaction is not affected.

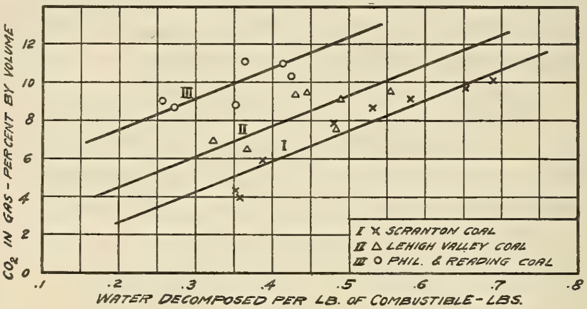

FIG. 20

It is probable that the difference in the catalytic action of different fuels, such as were enumerated above, may be very great. It is also probable that this effect is not so great between the same types of fuel, as, for example, between two grades of anthracite, or between two grades of coke. The ash in the fuel, as above noted, may also have a decided effect upon this action.

The difference in the catalytic action of charcoal, coke and anthracite is illustrated by Fig. 21, 22, and 23, which are taken from Dr. Clement's work, "On the Rate of Formation of CO in Gas Producers".[1] The results were obtained by passing CO_2 over charcoal, coke, and anthracite coal, respectively. In each case the material was ground to a certain size, about 0.2 in. on the side, and placed in a porcelain tube that could be maintained at different temperatures by means of an electric current, traversing a winding of nickel wire placed around the tube. The velocity of the gas, the per cent of CO formed, and the temperature of the tube were the variables. Fig. 21 shows the relation for charcoal between the per cent of CO formed and the velocity of the gas through the tube. Fig. 22 and 23 show the results for coke and anthracite coal, respectively. The velocity, which is the reciprocal of the time of contact, is expressed in feet per second.

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[1] Bull. No. 30, Eng. Exp. Sta., J. K. Clement, L. H. Adams and C. N. Haskins.

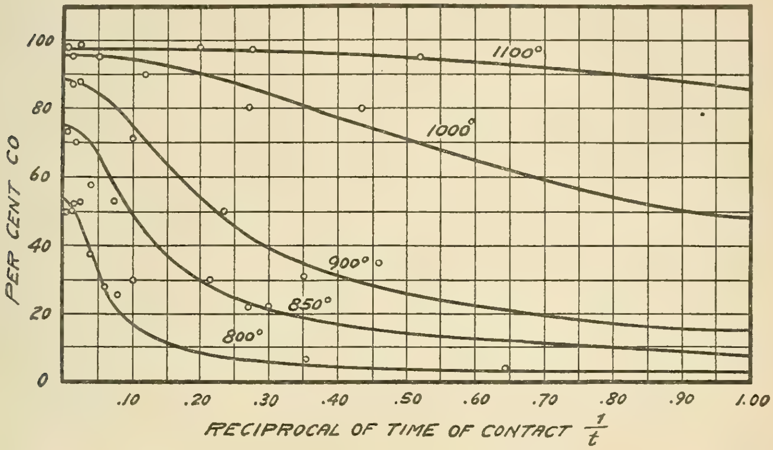

FIG. 21

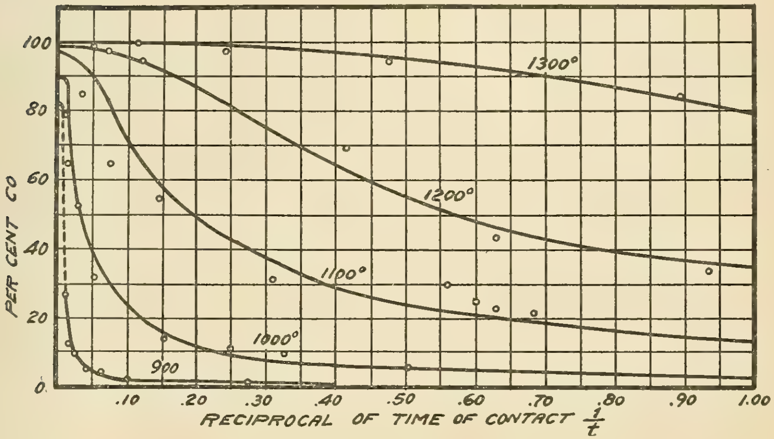

FIG. 22

It will be seen from these figures that the percentage of CO formed by the reaction $CO_2 + C = 2\,CO$, depends upon the temperature, upon the velocity or the reciprocal of the time of contact of gases with fuel, as it has been expressed on the figures, and upon the catalytic action of the fuel. This latter effect is shown by the difference in the per cent of CO formed at the same temperature and under the same velocity for the different fuels used

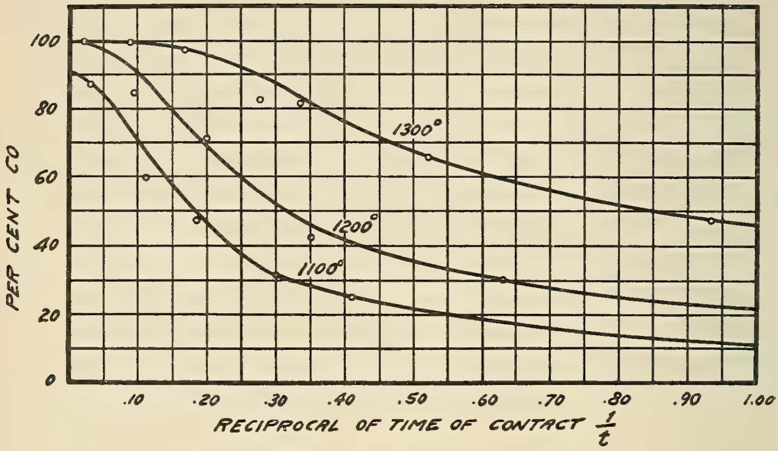

FIG. 23

in the experiments. For charcoal, Fig. 21, the per cent CO for a velocity of 1 ft. per second and a temperature of 1100° C., is 85 per cent, for coke and anthracite the percentages under the same condition, (Fig. 22 and 23) are 9 and 11 respectively. For a temperature of 1300° C. and a velocity of 1 ft. per second the percentages of CO formed are 100, 74, and 45 for the above fuels.

Tests 18, 19, 24 and 25 have been selected as representing most decidedly the effect of the size of the fuel upon the results of the performance of the producer.

Tests 19 and 24 were run under practically the same operating conditions, the only known variable being the size of the fuel, catalytic action excepted. Tests 18 and 25 were also run under essentially the same conditions of operation, with the size of the fuel constituting the only known variable. The principal results of the tests have for convenience been transferred from Table 5 to Table 6.

TABLE 6

1	Test No.	19	24	18	25	23
2	Fuel.	Lehigh	Scranton	Lehigh	Scranton	Scranton
	Size of fuel, mean diameter in in.	1½	½	1½	½	½
3	Capacity in cu. ft. per hr.	2730	2941	4545	4795	2980
4	Water decomposed per lb. of combustible	.429	.358	.446	.355	.689
5	Ratio of water decomposed to water supply	.323	.429	.408	.639	.402
6	Per cent CO_2 in the gas	9.4	4.04	9.44	4.2	10.15
7	Per cent H_2 in the gas	9.3	10.80	8.95	10.40	16.96
8	Per cent CO in the gas	17.43	27.3	17.13	27.01	17.39
9	B.t.u. per cu. ft. (High)	106.9	138.2	101.5	138.1	128.8
	(Low or effective)	101	131.6	96.0	131.7	119.4
10	Cold gas efficiency based on 100 per cent grate efficiency (High)	66.9	77.2	72.7	79 9	75.4
	(Effective)	63.3	73.5	68.6	70.3	69.8
11	Per cent loss in sensible heat and in moisture	19.3	12.7	22.7	14.8	15.3
12	Unaccounted-for loss	11.6	9.4	2.1	4.4	6.9
13	Temperature of gases leaving the producer °F	970	809	1201	1108	800
14	Temperature in the fuel bed °F, average..	2200		2300	2300	1740
15	Equivalent velocity of gas, feet per second	8.7	3.14	14.46	5.12	2

It will be seen from this table that the per cent of CO_2 for tests on the Lehigh chestnut is about 9.4 per cent, while the per cent CO_2 for the tests on the Scranton pea is about 4 per cent. The heating value of the gas is low in the former tests, as is also the efficiency, while the temperature is a little high. The relative percentage of CO_2 in the gas in the case of these tests is therefore to a certain extent a measure of efficiency of the producer.

The difference in the percentage of CO_2 appearing in the gas from the two coals in the tests under consideration may be due to two causes, viz., (a) the difference in the catalytic action of the two fuels, as above discussed, and (b) the difference in the size of the fuel. In the case of the Scranton pea which, as has been noted, would pass a ¾-in. mesh, the amount of catalytic surface exposed to the action of the gases is much greater than the surface exposed in the case of the Lehigh coal, which will pass over a 1¼-in. mesh and through a 2-in. mesh. The following will illustrate this. The mean diameter of the Scranton coal may be taken as ½ in., the mean diameter of the Lehigh coal may be taken as 1½ in.; since the number of pieces contained in a given volume is inversely as the cube of the mean diameter, and since the surface of each piece is directly as the square of the mean diameter, the ratio of the total surfaces exposed in the fuel bed of the producer will be as 3 and 1 for the Scranton and Lehigh coals, respectively.

Theoretically, the size of the fuel will have no effect upon the velocity of the gas through the fuel bed for the same rate of gasification. This is due to the fact that the number of pieces of coal required to fill the producer varies inversely as the cube of the mean diameter of the pieces, while the volume of each separate piece varies directly as the cube of the mean diameter, the volume of the coal present, and the volume of voids; consequently, the velocity of the gas through the fuel bed is independent of the size of the fuel.

That the voids are, in the case of the two coals, practically of the same volume, has been determined by water displacement. The volume of voids, in the case of the Scranton coal, was found to be 46 per cent of the volume occupied by the coal and 43 per cent for the Lehigh. The velocity of the gases through the fuel bed is therefore practically the same for the two coals for the same temperature and rate of gasification. The amount of draft required to drive the gases through the bed will, however, be different, owing to the increased frictional resistance due to the smaller voids in the Scranton coal.

The purely mechanical effect of the increase in the size of the fuel will be, from the above, if the volume of the fuel bed remain constant, to decrease the area of surface exposed to the gases, to decrease the number of pieces of coal in the path of the gases, and to decrease the drop in the pressure of the gases through the fuel bed.

The decrease in the drop in pressure may be assumed to have no effect upon the composition of the escaping gases within wide limits. The extent of the effect of decreasing the area of the catalytic surface exposed to the gases and of decreasing the number of pieces of coal in the path of the gases upon the composition of the producer gas generated and upon the reaction within the fuel bed is unknown. Dr. Clement's work shows the effect of the velocity of the gases upon the reaction of CO_2 with incandescent carbon. Our tests No. 24 and 25, Table 6, on the Scranton coal, seem to show the effect of the velocity of the gases on the performance of the producer, tests 18 and 19 also show the same. It will be noted from the above that the increase in the rate of gasification of about 100 per cent has not resulted in any marked change either in the composition, or the heating value of the gases in the case of tests 24 and 25. Tests 18 and 19 on the Lehigh coal show a slightly greater difference, and it is believed this is due to the lesser catalytic surface which results in a shorter time of contact of gases with fuel. From these tests and the curves of Fig. 21, 22 and 23, and beyond the velocity of 1 ft. per second (the curves are drawn only to this velocity) which corresponds to the velocity of the gases obtaining in the fuel bed of the producer, it will be seen that the effect of the velocity on the reaction of CO_2 on carbon is small.

As before pointed out, the difference in the velocity of gases through the fuel bed for the same rates of gasification for the two fuels, if any, must be small. The great difference in the CO_2 or in the composition of the gases from the two fuels for the same rates of gasification as above noted, must therefore be due to one or more of the following causes: (1) to the greater catalytic surface exposed to the gases as in the case of the Scranton coal; (2) to the greater number of CO_2 molecules coming in contact with the coal, due to the greater number of pieces; (3) to the smaller size of the voids in this coal which would tend to cause a more intimate mixture of gases with the coal; or (4) to a greater catalytic effect. It has been remarked that it is probable that the difference in catalytic action between two grades of anthracite coal is small. We will therefore assume that the difference in composition of the gases from the two fuels under discussion, when the rates of gasification and operating conditions are the same, is due to the difference in the amount of surface exposed to the action of the gases or to the difference in the number of pieces of coal in the path of the gases or to a combination of the two, or, in other words, to the effect of the size of the fuel.

The above conclusion is also supported by operating experience. Shallow fuel beds, which are equivalent to the use of large fuel, or small catalytic surface, produce high CO_2, high temperature of gases and low CO. The tests 18 and 19 show these conditions. The efficiency does not drop off, consequently the temperature of the gas is not high; for the excessive heat liberated, as evinced by the high CO_2, is utilized in the production of hydrogen.

16. *The Effect of Capacity.*—The effect of capacity, or of the rate of gasification upon the efficiency of the producer, when operating with the different fuels, is illustrated by Fig. 24, 25 and 26.

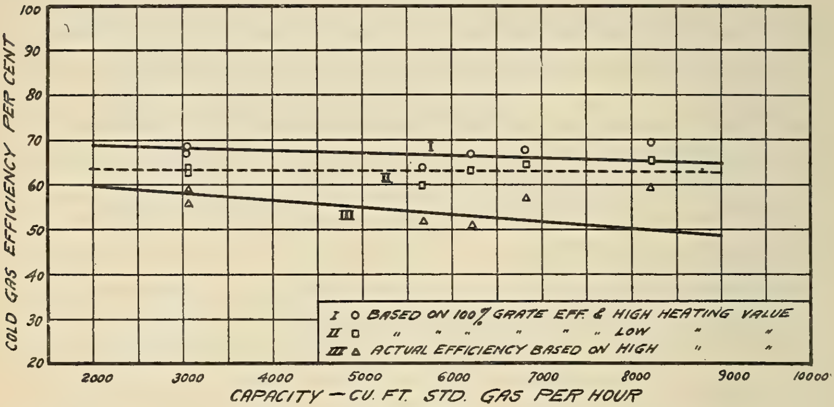

FIG. 24
CAPACITY—EFFICIENCY CURVES FOR PHILADELPHIA AND READING COAL

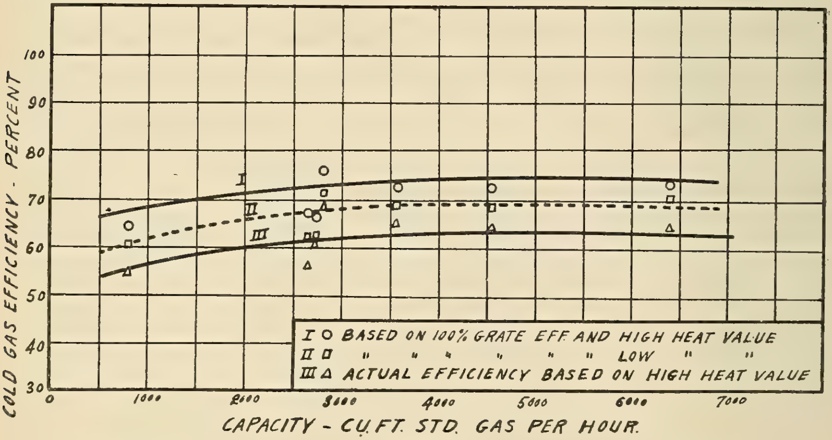

FIG. 25
CAPACITY—EFFICIENCY CURVES FOR LEHIGH VALLEY COAL

As there were only three tests for the gas house coke, no curves have been plotted from these tests. For each of the other fuels, three curves have been plotted, one for the actual efficiency based on high heating value of the gas, one for the efficiency based on 100 per cent grate efficiency, or, which is the same, based on combustible and upon the high heating value of the gas, and a third based on combustible and the low heating value of the gas. This latter curve is shown dotted on the figures.

Fig. 24 shows the curves for the Philadelphia and Reading coal. The curve for the actual efficiency drops off at the higher capacities. This is principally due to the more rapid formation of clinker, as the capacity and the temperature increase, which results in the necessity for more frequent poking, consequently, a much higher grate loss. The curve for efficiency based on 100 per cent grate efficiency and the high heating value of the gas drops off slightly. The curve based on 100 per cent grate efficiency and upon low heating value is practically a straight line.

The curves of Fig. 25 show the results for the Lehigh Valley coal. The drop in the curve for the lower capacities is partially due to the sensible heat lost to the producer walls and fuel bed, on account of the lower temperature of the fuel bed at the start of the test. This has been pointed out in the discussion of the unaccounted-for losses. If a correction were made for this unaccounted-for loss, the curves would approach a straight line. The drop at the other end of the curve is largely due to the effect of the velocity of the gases through the fuel bed, or to the shorter time of contact of gases with fuel owing to the larger size of this fuel.

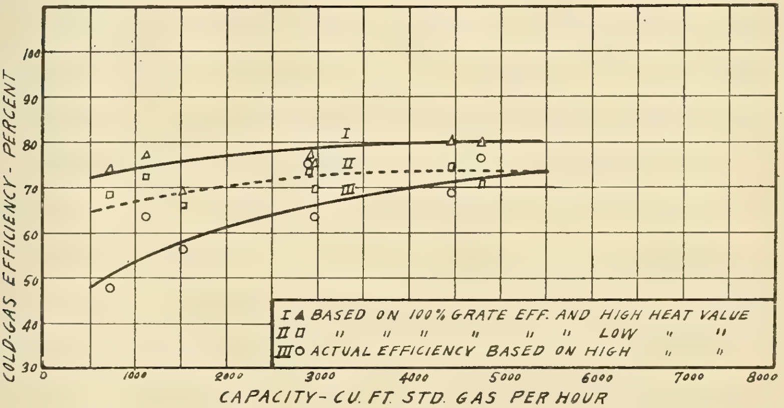

FIG. 26
CAPACITY—EFFICIENCY CURVES FOR SCRANTON PEA COAL

The curves for the Scranton pea coal, Fig. 26, show very little tendency to drop off at the highest capacity. This, it is believed, is explained by the small size of the fuel, consequently, by the larger area of fuel surface exposed to the gases.

The rapid falling off of the actual efficiency curve on these tests is due to the sensible heat lost to the producer walls and fuel bed as previously noted, and also to the fact that in the case of the Lehigh and Scranton coals, which had no tendency to clinker, that the weight of ash and refuse tended to remain constant and was independent of the capacity. As the composition of the ash and refuse remained constant, the actual grate loss tended to remain constant, which would, therefore, cause the actual efficiency at light loads to drop off. The curve based on 100 per cent grate efficiency is practically a straight line slanting toward the low capacities; this slant is also due to the sensible heat lost to the walls and the fuel bed of the producer.

The results of Table 6 bear out the conclusion drawn from the curve as to the effect of capacity. These results together show that capacity, or the rate of gasification, within very wide limits has little effect upon either the efficiency, the composition of the gas, or upon the heating value, so long as the steam supplied to the producer is so regulated as to maintain the same temperature within the fuel bed.

17. *Coal Per Square Foot of Grate Area*—The weight of coal gasified per square foot of grate area is related directly to the rate of gasification and depends upon this. Owing to the general use of the term and to the interest attached thereto by engineers, it probably merits a separate discussion.

It will be seen from Table 5, item 66, that this quantity varies in the tests on the Lehigh and Scranton coals from 7.67 lb. per hour, in the case of test 21, to 49.8 lb. in the case of test 17. Within this range, the producer has been operated with satisfactory results.

Anthracite producers in this country are rated on a basis of from 10 to 15 lb. of coal per sq. ft. of grate area per hour by the manufacturers. In European practice, the rating is from 20 to 30 lb. of coal per square foot of grate area. This difference in rating is doubtless due to the difference in the fuels used in the two countries.

From the results of the present tests, it must be concluded that the coal gasified per square foot of grate area depends almost entirely upon the nature of the coal. Were it not for practical considerations there seems to be no reason why the coal gasified should depend upon any condition other than the depth of the fuel bed. From the works of Dr. Clement previously referred to, and of Boudouard and others, it will be seen that a certain length of time is required for the completion of the reaction within the fuel bed of the producer, also that the time required for their completion depends upon the temperature and upon the catalytic action of the fuel. Consequently, in order to attain high rates of gasification, it is necessary that the fuel bed be increased in depth in order that the proper time of contact of gases with fuel obtains.

In the actual operation of the producer with a given depth of fuel bed, the coal gasified per square foot of grate area depends upon the amount of ash, the nature of the coal, and upon the catalytic action of the fuel.

The larger the percentage of ash in the fuel, the more frequently the producer requires cleaning, so that with high rates of gasification the removal of the ash alone would place a limit. The nature of the ash, that is, the temperature of fusing, also places a limit for a given depth of fuel bed. An ash fusing at a low temperature requires a low temperature within the fuel bed of the producer. This results in requiring a longer time of contact of gases with fuel in order that the reaction within the fuel bed may be completed. A fuel with slow catalytic action produces the same result.

Since, from the above, the coal gasified per square foot of grate area depends upon the depth of the fuel bed, we have used the expression "rate of descent of dry coal through the fuel bed" or " coal burned per cubic foot of fuel bed", to express the performance of a producer in addition to the expression under discussion.

18. *Clinker.*—The formation of clinker is due to the presence of incombustible matter in the ash which fuses at the temperature maintaining in the fuel bed of the producer. There are two ways of dealing with this, the more practical one being the operation at such capacities and with such an amount of water, or CO_2, in the case of the carbon monoxide producer, as to keep the temperature below that of the fusing point of the earthy matter contained

in the fuel. In doing this, the efficiency of the producer will be somewhat lowered, as the reaction of CO_2 on carbon will be greatly lessened, and large quantities of steam must be used to keep the temperature down, through the formation of hydrogen and the heating of the moisture that escapes decomposition. The heating of this moisture results in the lowering of the efficiency of the producer. The curves of Fig. 27, 28 and 29 indicate that the

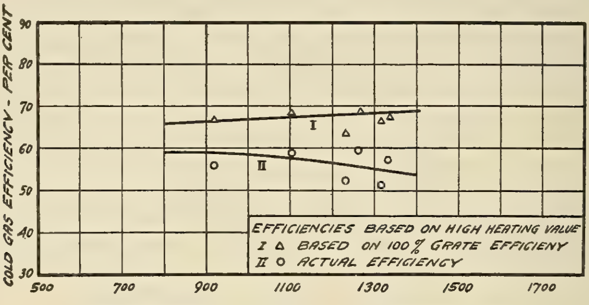

FIG. 27

TEMPERATURE—EFFICIENCY CURVES FOR PHILADELPHIA AND READING COAL

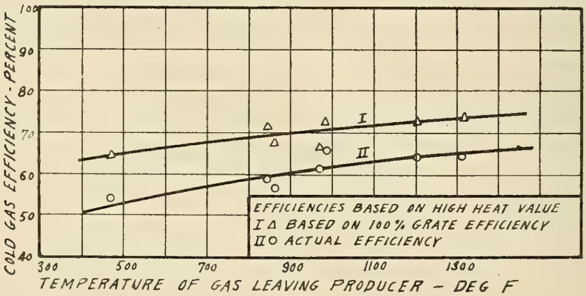

FIG. 28

TEMPERATURE—EFFICIENCY CURVES FOR LEHIGH VALLEY COAL

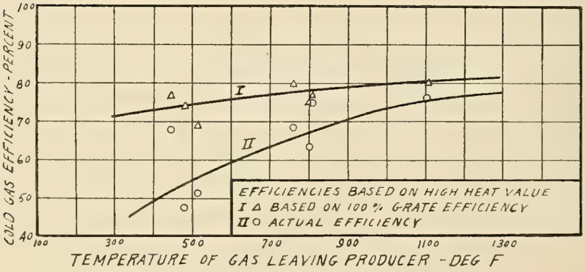

FIG. 29

TEMPERATURE—EFFICIENCY CURVES FOR SCRANTON PEA COAL efficiency of the producer tends to increase with the higher temperatures of operation. This increase, however, is comparatively small within certain limits and since reliability of operation is the desideratum, and not necessarily efficiency, the obvious means of decreasing the irregularities due to the formation of clinker is by operating at lower temperatures.

It is possible that fuels may be found in which the formation of clinker begins at a temperature so low as to prevent the reactions within the producer taking place. This is, however, not probable. The water vapor in practically every case tends to disintegrate both fuel and clinker. If an excess is used, it will tend to cause the fuel bed to become mushy and will result in poor gas, and a shut-down if engines are operating on the gas.

A second method of dealing with a coal containing a fusible ash is to add a flux in the form of a limestone or other cheap material which will render the clinker so fusible as to cause it to run from the fuel bed of the producer. Test 14 on the Philadelphia and Reading coal was run in this manner. It was determined from an analysis of the ash that about 60 lb. of limestone ($CaCO_3$) would be required per 100 lb. of coal in order to form a highly fluid clinker. The fuel charged on this test was, therefore, mixed with limestone in the ratio of 100 lb. of coal to 60 lb. of limestone. As the limestone when heated gives out 44 per cent of its weight in CO_2, this CO_2 takes the place of the water vapor and keeps the temperature down through the CO_2, reacting on the C to form CO.

The efficiency of the test is low, due partly to the absorption of heat in driving off the CO_2 from the limestone, but largely to the loss through the difference in temperature of the fuel bed at the start and close of the test. The graphical log sheet, Fig. 30, shows the uniformity of conditions that maintained. The fuel bed required practically no poking during the test, as the clinker fused with the limestone and trickled into the ash pit. At the close of the test, however, when the fire doors were opened for cleaning, the entire fuel bed "froze", and had to be broken up at the expense of considerable time and labor.

The above method is mentioned simply as a matter of interest, and indicates a possible though hardly practical means of dealing with clinker.

19. *Weight of Water Required for the Producer.*—The weight of

water required by the producer depends very largely on the fuel that is being used, and to a certain extent upon the proportions of the producer.

With a fuel that has no tendency to clinker, the highest efficiency will be obtained by using such an amount of water as

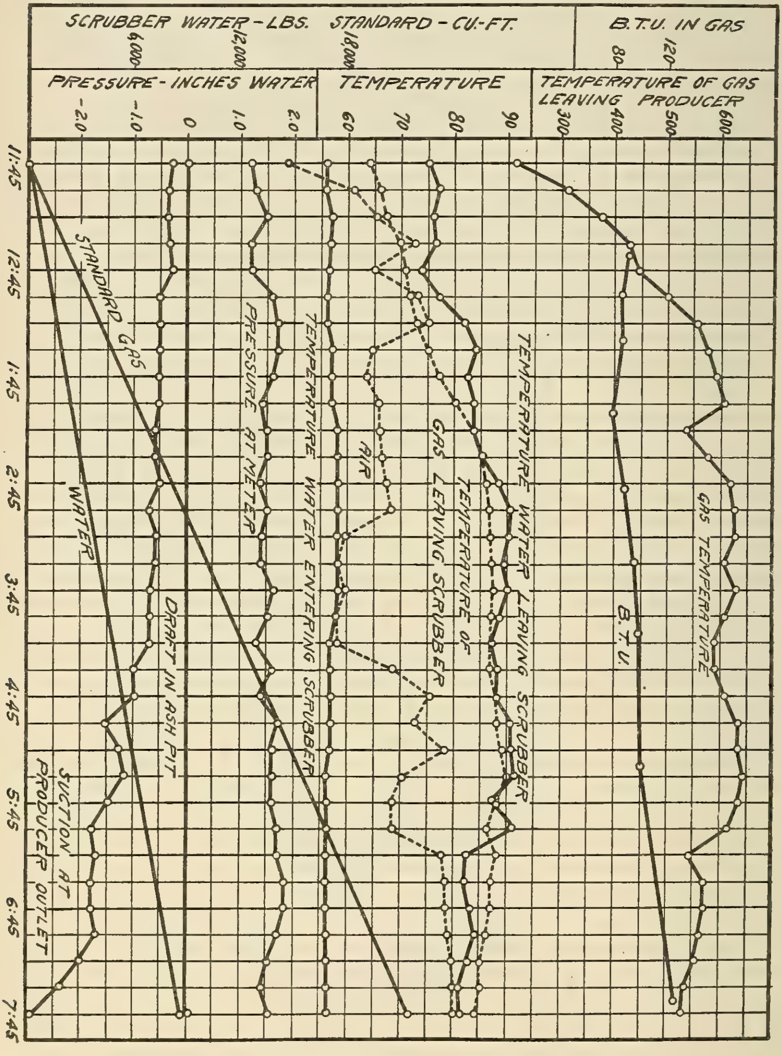

FIG. 30

to result in between 2 and 4 per cent CO_2 in the gas leaving the producer. This of course, requires a deep fuel bed and a high temperature within the decomposition zone to insure the completion of the CO reaction. It is a condition of operation that can scarcely be obtained in a producer as small as the one that has been used on the present tests, for the reason that while there may be no formation of clinker, there will be, owing to the small diameter of the fuel bed, a tendency for the fuel to pack, which will necessitate poking from time to time in order to insure the proper descent of the fuel.

This packing or arching of the fuel, as it decreases the time of contact of gases with fuel, results in increasing the percentage of CO_2, and raising the temperature of the gases, which tends to lower the efficiency. If the producer had been provided with some form of shaking grate, which is quite possible in producers of this size, the efficiency would have been increased several per cent and the uniformity of operation increased much more.

In the case of fuels containing an ash fusing at temperatures close to 2200° F., it will be necessary to use sufficient water to lower the temperature of the fuel bed below that temperature at which the formation of clinker begins. This may result in a slightly lower efficiency of operation, but as it is usual that such operation is necessitated through the use of a poor, consequently a cheap fuel, the efficiency is of less importance than the reliability of operation. In the case of such operation, the hydrogen in the gas will be high, the CO_2 high and the CO low.

Test 23 of Table 6 as compared with Test No. 24 shows the effect of operating with a large quantity of moisture, on the CO_2, heating value and efficiency.

As has been indicated a number of times, the reaction of water on incandescent carbon to form hydrogen takes place much faster at the lower temperature than does the CO reaction, consequently, when a producer is operating with a shallow fuel bed, or with a larger fuel, as in the case of the Lehigh coal, or with a fuel of slow catalytic action, in order to keep down the temperature of the gases and to keep up the efficiency, it will be necessary to use larger quantities of water than would be the case when operating with a deeper fuel bed, as there will be insufficient time for the completion of the CO reaction unless the producer is operated at a greatly lowered capacity.

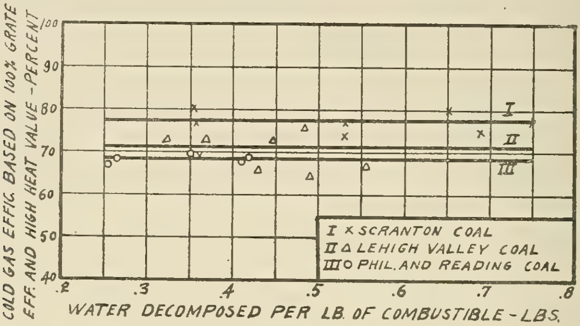

FIG. 31

The curves of Fig. 31 show that within the accuracy and range of these tests, there is practically no effect upon the efficiency of the producer due to the increase of the water decomposed.

If the range were increased in either direction, there would be a great falling off in efficiency.

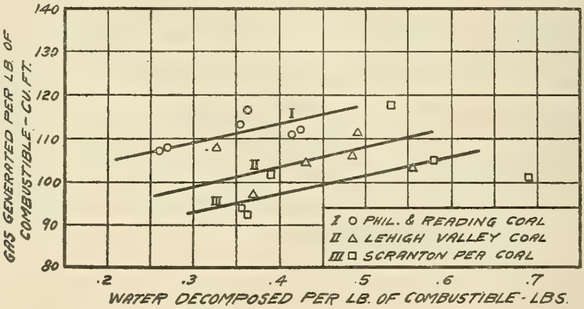

FIG. 32

Fig. 32 shows the effect of the water decomposed per pound of combustible upon the volume of gas generated per pound of combustible, and Fig. 33 shows the effect of the gas generated per pound of combustible upon the heating value of the gas per cu. ft.

20. *The Effect of Fuel Bed Temperature.*—The effect of the fuel bed temperature upon the composition of producer gas and upon the efficiency of the producer from the previous discussion has been pointed out. From the results of Harries' experiments, (see page 6), the experiments of Dr. Clement, illustrated

by Fig. 21, 22, and 23, and from the results of Boudouard's experiments, the general effect of the fuel bed temperature can be predicted with considerable certainty. The exact effect, as it depends upon the catalytic action of the fuel, the size of the fuel, and other variables, can not, however, be determined for the different fuels without direct experiment. Within comparatively wide limits, and, speaking in general, the efficiency of the producer, as has been pointed out, is practically independent of the amount of steam fed to the producer or the amount of H_2 in the gas. With low fuel bed temperatures, it will be seen from Dr. Clement's curves that the CO will be low and the CO_2 high. From the experiments of Harries, it will be seen that the reaction of H_2O on carbon has reached equilibrium at a temperature as low as 1240° F. with 8.41 per cent of H_2 formed. So therefore in the formation of H_2 at low temperatures and the formation of CO at the higher temperatures, the principal effect of changing the temperature of the fuel bed is to cause a shifting in the relative percentage of CO, CO_2, and H_2 present in the gas generated. If the change is so made that there is no great difference in the temperature of the leaving gases, the efficiency of the producer is very slightly affected. Tests 23 and 24 of Table 6 illustrate this. The fuel bed temperature in the case of test 23 is 1740°F., the tem-

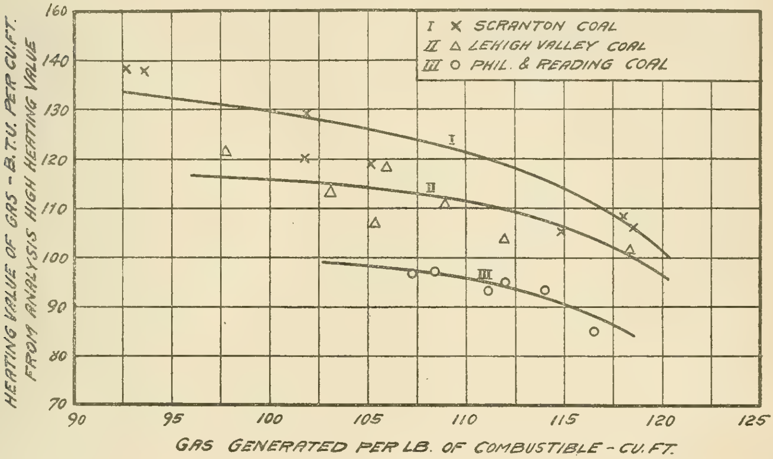

FIG. 33

perature of the fuel bed for test 24 is approximately 2200°F. The temperature of the gases leaving the producer is practically the same, as is also the efficiency. The percentage of CO has shifted from 27.3 to 17.39, while the H_2 has shifted from 10.8 to 16.96 per cent. The heating value of the gas for the lower temperature has fallen off, while the number of cubic feet of gas per pound of combustible has increased from 92.6 for test 24 to 101.41. This latter is due to the lesser density of the hydrogen.

The fuel bed temperatures, as obtained for the different tests, are given in Table 3.

The radiation and conduction losses will probably not exceed 1 per cent. The loss due to tar and soot and to the absorption of the gases by the scrubber water will not exceed 1 per cent. The losses due to the difference between the initial and final temperatures of the fuel bed are variable and depend upon the capacity and to a certain extent upon the length of time required to blow the fires and produce a gas sufficiently rich for operating conditions. These losses have been discussed on page 37, and it was shown here that they would doubtless vary from .5 to about 9 per cent, depending upon the above conditions.

The experimental errors made in the measurement of different quantities may be either positive or negative and the magnitude of the probable error varies from about 2 or 3 per cent in tests at capacities between 4000 and 2800 cubic feet of gas per hour to between 4 and 7 per cent for tests between 2000 and 750 cubic feet per hour.

IV. CONCLUSIONS

1. A producer of the size and type tested is a practical piece of apparatus. With proper care in operating, and in the selection of the fuel, it is also a reliable piece of apparatus possessed of a fair degree of efficiency.

2. The efficiency of the producer is, within wide limits, practically independent of the rate of gasification.

3. The efficiency of the producer, within comparatively wide limits, is only slightly affected by the relative percentages of H_2 and CO appearing in the gas. With low temperature in the fuel bed, due to the use of a large quantity of steam, there is a high percentage of H_2 and CO_2. With high temperature in the fuel bed, the H_2 and CO_2 drop off while the CO increases.

4. From the above, it follows that the amount of steam to be used under any given conditions depends entirely upon the nature of the fuel. Clinkering coals require large quantities of steam in order to keep the temperature below that of the formation of clinker, while non-clinkering coals require much less steam.

5. The size of the fuel for a given temperature of fuel bed and a given depth of fuel bed has a marked effect upon the heating value and composition of the gas, and upon the efficiency of the producer. An increase in the size of fuel tends to cause the efficiency, heating value of the gas, and the percentage of CO to drop off.

6. The graphical logs show that the conditions (with the exception of the tests on Philadelphia and Reading coal) were sufficiently uniform to prevent trouble in the operation of engines driving machinery that requires no great degree of sensitiveness in regulation, such as the driving of pumping machinery, or shafting for machine shops, provided these engines have overload capacities of from 15 to 20 per cent. The conditions were not sufficiently uniform to permit the use of the gas in engines designed to drive electric lighting and other machinery requiring sensitive regulation. This is due, however, to the very small size of the unit. With larger units, the uniformity has proved entirely sufficient for the operation of engines driving electric generators.

7. From item 111 of Table 5, it will be found that the volume of gas generated per lb. of coal averages about 76 cu. ft. The average low heating value of the gas, if the tests on the Philadelphia and Reading coal are not used, is approximately 110 B. t. u. per cu. ft. Since the average engine requires about 10,500 effective B. t. u. per b. h. p. hr., 95 cu. ft. of this gas will be required per b. h. p. hr. or $\frac{95}{76} = 1.25 +$ lb. coal. Since the coal contains about 12,800 B. t. u. per lb., the efficiency of the plant will be $\frac{2545 \times 100}{12800 \times 1.25} = 16$ per cent. approximately. The thermal efficiency of a steam plant of this same size will be about 3 per cent, assuming a boiler efficiency of 60 per cent and an engine efficiency of 5 per cent.

If the anthracite fuel costs \$5.00 per ton, soft coal for the steam plant must cost \$0.94 per ton in order that the fuel cost remain the same per h. p. hr. The cost of attendance, maintenance and repair will be practically the same for each plant.

8. Under the above conditions, with anthracite at \$5.00 per ton, one b. h. p. could be produced at a fuel cost of .31 cent per hr., or 3.7 cents per 12 hrs.

9. The effect of the capacity, the amount of steam used, the effect of the size of the fuel, the amount of CO_2 in the gas, and other items of a general nature, and the conclusions drawn from such items,are entirely applicable to producers of all sizes. It is believed that these items, with the forms and formulas, constitute the most valuable portions of this paper.

APPENDIX

APPENDIX*

FORM 1 RESULTS OF GAS PRODUCER TRIALS

1 Test number..........
2 Made by..........
3 At..........The University of Illinois..........
4 Kind of producer..........Otto..........
5 To determine..........Efficiency..........
6 Principal conditions governing trial....Uniform load..........
7 Kind of fuel..........Scranton-Anthracite,..........
8 Kind of grate..........Plain..........
9 Method of starting and stopping test....Alternate..........
10 Type of producer..........Suction..........
11 Form of blower-ejector..........Schutte & Koerting..........
12 Date of trial..........
13 Duration of trial..........

DIMENSIONS AND PROPORTIONS

14 Dimensions of grate, ft..........
15 Grate area, sq. ft..........
16 Mean diameter of fuel bed, ft..........
17 Depth of fuel bed, ft..........
18 Area of fuel bed, sq. ft..........
19 Height of discharge pipe above grate, ft..........
20 Approximate width of air spaces in grate, inches..........
21 Area of air space, sq. ft..........
22 Proportion of air space to whole grate area, per cent..........
23 Area of discharge pipe, sq. ft..........
24 Water heating surface in vaporizer, sq. ft..........
25 Outside diameter of shell, ft..........
26 Length of shell from base to top of magazine, ft..........
27 Ratio of water heating surface to grate area,—to 1..........
28 Ratio of minimum draft area to grate area, 1 to..........

AVERAGE PRESSURES

29 Draft in ashpit, inches, water..........
30 Suction at producer outlet, inches, water..........
31 Pressure at meters, inches, water..........
32 Corrected barometer reading..........
32.1 Steam pressure, lb. per sq. in. gage..........

AVERAGE TEMPERATURES

33 Of fire room, deg. Fahr..........
34 Of steam leaving vaporizer, deg. Fahr..........
35 Of feed water entering vaporizer, deg. Fahr..........
36 Of overflow from vaporizer, deg. Fahr..........
37 Of water entering scrubber, deg. Fahr..........
38 Of water leaving scrubber, deg. Fahr..........
39 Of gases leaving producer, deg. Fahr..........
40 Of gases leaving scrubber, deg. Fahr..........
41 Of gases entering meter, deg. Fahr..........

FUEL

42 Size and condition..........
43 Weight of coal as fired, lb..........
44 Percentage of moisture in coal..........
45 Total weight of dry coal fired, lb..........

---

*In the following Appendix, the forms used in computing the results are given for the benefit of those who may have occasion to use them in the working of results of producer tests. The use of the forms has been explained on page 38.

46 Total ash and refuse, lb.
47 Quality of ash and refuse
48 Total combustible consumed, lb
49 Percentage of ash and refuse in dry coal

PROXIMATE ANALYSIS OF COAL

50 Fixed carbon
51 Volatile matter
52 Moisture
53 Ash
54 Sulphur, separately determined

ULTIMATE ANALYSIS OF DRY COAL

55 Carbon, C
56 Hydrogen, H_2
57 Oxygen, O_2
58 Nitrogen, N_2
9 Sulphur, S
60 Ash
61 Moisture in sample of coal as received

ANALYSIS OF DRY ASH AND REFUSE

62 Carbon, per cent
63 Earthy matter, per cent
  a SiO_2
  b Al_2O_3
    Fe_2O_3
  c MgO
  d CaO

FUEL PER HOUR

64 Dry coal fired per hr. lb
65 Combustible consumed per hr. lb
66 Dry coal per sq. ft. of grate area per hr. lb
67 Combustible per sq. ft. of grate area per hr. lb
68 Dry coal per sq. ft. of fuel bed per hr. lb.
69 Combustible per sq. ft. of fuel bed per hr. lb
70 Rate of descent of dry coal through fuel bed, lb per ft. per sq. ft. per hr
71 Rate of descent of combustible through fuel bed, lb. per ft. per sq. ft. per hr.

CALORIFIC VALUE OF FUEL

72 Calorific value by oxygen calorimeter per lb. dry coal, B. t. u
73 Calorific value by oxygen calorimeter per lb. of combustible B. t. u
74 Calorific value by analysis per lb. dry coal, B. t. u
75 Calorific value by analysis per lb. of combustible, B. t. u

WATER

76 Total[1] weight of water fed to vaporizer, lb
77 Total weight of overflow from vaporizer, lb
78 Water[1] actually evaporated in vaporizer, lb
79 Total weight of water fed to producer, lb
  a From vaporizer[1]
  b In air
  c In coal
80 Total weight of water decomposed.
81 Total weight of water in gas leaving producer, lb
82 Ratio of water decomposed to water supplied
83 Weight of water decomposed per lb. gas generated, lb

---

[1] Steam fed to producer, where vaporizer is not used.

84 Weight of water decomposed per lb. of dry coal fired, lb. ....
85 Weight of water decomposed per lb. of combustible consumed, lb............
86 Weight of water decomposed per lb. of air supplied, lb.........................
87 Weight of water supplied per lb. of dry coal fired, lb.........................
88 Weight of water per lb. of combustible consumed, lb...........................
89 Weight of water supplied per lb. of dry air used, lb...........................
90 Total weight of scrubber water, lb...

WATER PER HOUR

91 Water evaporated per hr. in vaporizer, lb..
92 Water evaporated per hr. per sq. ft. of water heating surface in vaporizer, lb.
93 Weight of water decomposed per hr., lb...
94 Total weight of water fed to producer per hr., lb..............................
95 Weight of scrubber water used per hr., lb..

QUANTITY OF AIR

96 Per cent of moisture in air, per cent of dry air...............................
97 Total weight of dry air, lb...
98 Total weight of dry air per hr. lb...
99 Weight of dry air used per lb. of dry coal fired, lb...........................
100 Weight of dry air used per lb. of combustible consumed, lb..................
101 Weight of dry air used per lb. of dry gas generated, lb.......................

GAS

102 Per cent moisture in gas leaving producer, per cent of dry gas...............
103 Per cent of soot and tar in gas leaving producer.................................
104 Calorific value of standard gas from analysis (high value) B. t. u. per cu. ft..
104a Calorific value of standard gas from analysis (low value) B. t. u..............
105 Calorific value of standard gas from calorimeter, (high value) B.t.u. per cu. ft.
106 Specific weight of standard gas, lb. per cu. ft...................................
107 Specific heat of dry gas leaving producer ....
108 Carbon ratio C/H...
109 Total volume standard gas, cu. ft...
110 Volume of standard gas per hr. cu. ft...
111 Volume of standard gas per lb. of dry coal...
112 Volume of standard gas per lb. of combustible....................................
113 Total weight of standard gas, lb...
114 Weight of standard gas per hr., lb...
115 Weight of standard gas per lb. of dry coal fired, lb.............................
116 Weight of standard gas per lb. of combustible consumed, lb..................

GAS ANALYSIS BY VOLUME

117 Carbon dioxide, CO_2...
118 Carbon monoxide, CO...
119 Oxygen, O_2...
120 Hydrogen, H_2...
121 Marsh gas, CH_4...
122 Olefiant gas, C_2H_4...
123 Sulphur dioxide, SO_2...
124 Hydrogen sulphide, H_2S..
125 Nitrogen, N_2, by difference..

EFFICIENCY

126 Grate efficiency, per cent..
127 Hot gas efficiency, based on high heating value, per cent......................
128 Cold gas efficiency, based on high heating value, per cent.....................
128a Cold gas efficiency, based on low heating value, per cent......................

EFFICIENCY BASED ON 100 PER CENT GRATE EFFICIENCY

128*b* Hot gas efficiency, based on high heating value, per cent..................
128*c* Cold gas efficiency, based on high heating value, per cent..................
128*d* Cold gas efficiency, based on low heating value, per cent..................

COST OF GASIFICATION

129 Cost of fuel per ton delivered in producer room..................
130 Cost per 1000 cu. ft. of standard gas, cents..................
131 Cu. ft. scrubber water per 1000 cu. ft. gas..................

POKING

132 Method of poking..................
133 Frequency of poking..................

FIRING

134 Method of firing..................
135 Average intervals between firing..................
136 Average amount of fuel charged each time, lb..................

HEAT BALANCE

DEBIT	B. T. U.
a Total heat supplied per lb. dry coal..............	
b Total heat supplied by air per lb. dry coal......	
c Total heat supplied by moisture in air per lb. dry coal..............	
d Total heat supplied by moisture in coal per lb. dry coal..............	
e Total heat supplied as sensible heat in coal per lb. dry coal..............	
f Total[1] heat supplied by water in vaporizer per lb. dry coal..............	
Total..............	

CREDIT	B. T. U.	Per Cent
a Heat contained as sensible heat in dry gas.....		
b Heat contained in moisture..............		
c Heat contained in dry gas (heat of combustion)		
d Heat in unburned carbon..............		
e Heat contained in ash and refuse as sensible heat		
f Heat lost in overflow from vaporizer..............		
g Heat lost in radiation and conduction..............		
Total..............		

FORM 2 RESULTS OF GAS PRODUCER TRIALS

NO. OF TEST DATE, TIME OF START,
TIME OF STOP DURATION OF TRIAL, HRS.
KIND OF FUEL.

DIMENSIONS AND PROPORTIONS

1 Dimensions of grate, ft..................
2 Grate area sq. ft..................

---

[1] Supplied in steam, where vaporizer is not used.

3 Mean diameter of fuel bed, ft
4 Depth of fuel bed, ft
5 Area of fuel bed, sq. ft
6 Height of discharge pipe above grate, ft
7 Approximate width of air spaces in grate, inches
8 Area of air space, sq. ft
9 Ratio of air space to whole grate area, %
10 Area of discharge pipe, sq. ft
11 Water heating surface in vaporizer, sq. ft.
12 Outside diameter of shell, ft
13 Length of shell from base to top of magazine, ft
14 Ratio of water heating surface to grate area —to 1
15 Ratio of minimum draft area to grate area to

AVERAGE PRESSURES

16 Average barometer reading, inches Hg
17 Average corrected barometer reading, inches Hg
18 Draft in ash pit, inches water
19 Suction at producer outlet, inches water
20 Absolute pressure at producer outlet, inches Hg
21 Suction[1] at orifice, inches water
22 Absolute pressure[1] at orifice. inches Hg
23 Pressure at meters, inches water
24 Absolute pressure at meters, inches Hg
25 Vapor pressure at meters, inches Hg
26 Dry gas pressure at meters, inches Hg
27 Suction at meter for dryer, inches water
28 Absolute pressure at meter for dryer, inches Hg

AVERAGE TEMPERATURES

29 At barometer, deg. Fahr.
30 Of fire room, deg. Fahr.
31 Of fire room, deg. absolute Fahr
32 Of steam, deg. Fahr.
33 Of feed water entering vaporizer, deg. Fahr
34 Overflow from vaporizer, deg. Fahr
35 Rise in vaporizer, deg. Fahr.
36 Of water entering scrubber, deg. Fahr
37 Of water leaving scrubber, deg. Fahr
38 Rise in scrubber, deg. Fahr
39 Of gases leaving producer, deg. Fahr
40 Of gases leaving producer, deg. abs. Fahr.
41 Of gases leaving first scrubber, deg. Fahr
42 Of gases leaving first scrubber, deg. abs. Fahr
43 Drop in temperature of gases in scrubber, deg. Fahr
44 Of gases entering meters, deg. Fahr
45 Of gases entering meters, deg. abs. Fahr
46 Of gas at meter at dryer, deg. Fahr
47 Of gas at meter at dryer, deg. abs. Fahr

FUEL

48 Size and condition
49 Weight of coal as fired, lb
50 Percentage of moisture in coal
51 Total weight of dry coal fired, lb

Steam pressure may be substituted here in case the water is not supplied from the vaporizer

52 Total ash and refuse, lb..........
53 Quality of ash and refuse..........
54 Total weight of combustible, lb..........
55 Percentage of ash and refuse in dry coal, per cent..........

PROXIMATE ANALYSIS OF COAL

56 Fixed carbon, per cent..........
57 Volatile matter, per cent..........
58 Moisture, per cent..........
59 Ash, per cent..........
60 Sulphur, separately determined, per cent..........

ULTIMATE ANALYSIS OF DRY COAL

61 Carbon, C, per cent..........
62 Hydrogen, H_2, per cent..........
63 Oxygen, O_2, per cent..........
64 Nitrogen, N_2, per cent..........
65 Sulphur, S, per cent..........
66 Ash, per cent..........
67 Moisture in sample coal as received, per cent..........

ANALYSIS OF DRY ASH AND REFUSE

68 Carbon, per cent..........
69 Earthy matter, per cent..........
a SiO_2
b $\left\{\begin{matrix}Al_2O_3\\Fe_2O_3\end{matrix}\right.$
c MgO
d CaO

FUEL PER HOUR

70 Dry coal fired per hr., lb..........
71 Combustible consumed per hr., lb..........
72 Dry coal per sq. ft. of grate area per hr., lb..........
73 Combustible per sq. ft. of grate area per hr., lb..........
74 Dry coal per sq. ft. of fuel bed per hr., lb..........
75 Combustible per sq. ft. of fuel bed hr., lb..........
76 Rate of descent of dry coal through fuel bed, lb. per ft, per sq. ft. per hr.......
77 Rate of descent of combustible through fuel bed, lb. per ft. per sq. ft. per hr..

CALORIFIC VALUE OF FUEL

78 Calorific value by oxygen calorimeter per lb. dry coal, B. t. u..........
79 Calorific value by oxygen calorimeter per lb. combustible B. t. u..........
80 Calorific value by analysis, per lb. dry coal, B. t. u..........
81 Calorific value by analysis, per lb. combustible, B. t. u..........

WATER

82 Total[1] weight fed to vaporizer, lb..........
83 Total weight of overflow, lb..........
84 Water[1] actually evaporated in vaporizer, lb..........
85 Weight of water fed to producer,
a From vaporizer[1]..........
b In air..........
c In coal..........
Total..........
86 Total weight of water decomposed from analysis, lb..........
87 Total weight of water decomposed as used in calculations, lb..........

---

[1] Steam fed to producer where vaporizer is not used.

88 Total weight of moisture in gas leaving producer, lb.........................
89 Ratio of water decomposed to water supplied............ ... .
90 Weight of water decomposed per lb. of gas generated, lb.... .. ..
91 Weight of water decomposed per lb of dry coal fired, lb.........................
92 Weight of water decomposed per lb, of combustible consumed, lb..............
93 Weight of water decomposed per lb. of air supplied, lb........................
94 Weight of water supplied per lb. of dry coal fired.lb...........................
95 Weight of water supplied per lb. of combustible consumed, lb.................
96 Weight of water supplied per lb. of air used, lb.................................
97 Total weight of scrubber water, lb............ ....
98 Total weight of water absorbed from sample by dryer, grams.................

WATER PER HOUR

99 Water evaporated per hr. in vaporizer, lb..
100 Water evaporated per hr. per sq. ft. of water heating surface in vaporizer, lb..
101 Weight of water decomposed per hr., lb............ ....
102 Total weight of water fed to producer per hr., lb...............................
103 Weight of scrubber water used per hr., lb........................ ....

QUANTITY OF AIR

104 Relative humidity of air, per cent..
105 Per cent of moisture contained in air, per cent by weight of dry air...............
106 Total weight of dry air by analysis, lb..
107 Total weight of dry air by orifice, lb..
108 Total weight of dry air as used in calculations, lb.............................
109 Weight of dry air per hr. from total used in calculations.......... ....
110 Weight of dry air used per lb. of dry coal fired, lb.............................
111 Weight of dry air used per lb. of combustible consumed, lb.....................
112 Weight of dry air used per lb. of dry gas generated, lb.........................

GAS

113 Volume of gas sample passing through meter at dryer, cu. ft....................
114 Volume of standard gas passing through meter at dryer, cu. ft..................
115 Total weight of gas passing through dryer meter, lb............................
116 Percentage of moisture in gas leaving producer, from dryer, per cent dry gas...
117 Percentage of moisture in gas leaving producer, from water fed to producer, per cent dry gas..... ....
118 Percentage soot and tar in gas leaving producer, per cent...... ....
119 Calorific value per cu. ft. standard gas from analysis B.t.u. (high value).........
119*a* Calorific value per cu. ft. of standard gas, by analysis (low value)..............
120 Calorific value per cu. ft. of standard gas from calorimeter, B.t.u. (high value)
121 Specific weight of standard gas, lb. per cu. ft...... ....
122 Specific heat of dry gas leaving producer ....
123 Carbon ratio C/H...
124 Total volume of gas from meters, cu. ft.. .....
125 Total volume of standard gas, from meters, cu. ft................... ....
126 Total volume of standard gas, from analysis, cu. ft...............................
127 Total volume as used in calculations, cu. ft.......................................
128 Volume of standard gas per hr. from total used in calculations.................
129 Volume of standard gas per lb. of dry coal from total used in calculations, cu. ft.
130 Volume of standard gas per lb. of combustible from total used in calculations, cu. ft.. ....
131 Total weight of standard gas from total used in calculations, lb................
132 Weight of standard gas per hr., lb...
133 Weight of standard gas per lb. of dry coal, lb.....................................
134 Weight of standard gas per lb. of combustible, lb.................................

GAS ANALYSIS BY VOLUME

135 Carbon dioxide, CO_2
136 Carbon monoxide, CO
137 Oxygen, O_2
138 Hydrogen, H_2
139 Marsh gas, CH_4
140 Olefiant gas, C_2H_4
141 Sulphur dioxide, SO_2
142 Hydrogen sulphide, H_2S
143 Nitrogen, N_2 by difference

GAS ANALYSIS BY WEIGHT

144 Carbon dioxide, CO_2
145 Carbon monoxide, CO
146 Oxygen, O_2
147 Hydrogen, H_2
148 Marsh gas, CH_4
149 Olefiant gas, C_2H_4
150 Sulphur dioxide, SO_2
151 Hydrogen sulphide, H_2S
152 Nitrogen, N_2 by difference

EFFICIENCY

153 Grate efficiency, per cent
154 Hot gas efficiency, based on high heating value, per cent
155 Cold gas efficiency, based on high heating value, per cent
155.1 Cold gas efficiency, based on low heating value, per cent

EFFICIENCY BASED ON 100 PER CENT GRATE EFFICIENCY

155*a* Hot gas efficiency, based on high heating value, per cent
155*b* Cold gas efficiency, based on high heating value, per cent
155*c* Cold gas efficiency, based on low heating value, per cent

COST OF GASIFICATION

156 Cost of fuel per ton delivered in producer room
157 Cost per 1000 cu. ft. of standard gas, cents
158 Cu. ft. scrubber water per 1000 cu. ft. standard gas

POKING

159 Method of poking
160 Frequency of poking

FIRING

161 Method of firing
162 Average intervals between firings
163 Average amount of fuel charged each time

HEAT BALANCE

DEBIT	B.T.U.
a Total heat supplied per lb. dry coal	
b Total heat supplied by air per lb. dry coal	
c Total heat supplied by moisture in air per lb. dry coal	
d Total heat supplied by moisture in coal	
e Total heat supplied as sensible heat in coal	
f Total[1] heat supplied in vaporizer water	
Total	

---

[1] Supplied in steam, where vaporizer is not used.

Credit	B.T.U.	Per Cent
a Heat contained as sensible heat in dry gas		
b Heat contained in moisture		
c Heat contained in dry gas (heat of combustion)		
d Heat in unburned carbon		
e Heat contained as sensible heat in ash and refuse		
f Heat lost in overflow from vaporizer		
g Radiation and conduction, by difference		
Total		

FORM 3 GUIDE SHEET CONTAINING ALL FORMULAS AND THEIR DERIVATION

The item numbers refer to the items of Form 2, and are arranged in the order of computation.

Item 4. "Depth of fuel bed" is to a certain extent arbitrary. In order that the term may have a fixed and definite meaning we will define it as the distance between the upper edge of the ash zone and that section of the fuel bed from which the gases separate and leave the fuel. The upper edge of the ash zone can ordinarily be readily determined by inspection.

Item 16. This reading is the average of the barometer readings for the test and is not corrected.

Item 17. Item 16 corrected. The following formula may be used:

Let H = corrected barometer reading.
t = temperature, deg. fahr.
h = barometer reading corresponding to temperature t.
Then $H = h\ (1.00254 - 0.000079t)$

Item 17. = Item 16 (1.00254 — 0.000079 × Item 29)
Item 18. = Observed.
Item 19. = Observed.
Item 20. = Item 17 — Item 19 × 0.0735
Item 21. = Observed.
Item 22. = Item 17 — Item 21 × 0.0735
Item 23. = Observed.
Item 24. = Item 17 + Item 23 × 0.0735
Item 25. = Taken from steam tables using temperature in Item 44, 1 lb. per sq. in. = 2.04 in. Hg.
Item 26. = Item 24 — Item 25
Item 27. = Observed.
Item 28. = Item 17 — Item 27 × 0.0735

Items 29 to 47 inc. The observed temperatures should be corrected from the calibration curves before being placed in Form 2. The absolute temperature = the observed temperature + 460 deg.

Item 39. This item is observed in deg. Cent. and should be transferred into deg. Fahr.

$$\text{Deg. Fahr.} = \frac{9}{5}\,\text{deg. Cent.} + 32$$

Each observation must be transferred.

Item 50. Taken from Item 67.

Item 51. $\text{Item 49}\left(1 - \frac{\text{Item 50}}{100}\right)$

Item 52. Taken from ash sheet, correction being made for any moisture taken up in the ash-pit.

Item 54. In these tests the total weight of combustible consumed will be taken as the total weight of dry coal fired, minus
the weight of ash computed from the analysis, minus
the weight of nitrogen — $\frac{9}{8}$ × the weight of oxygen, minus
the weight of carbon contained in the ash and refuse and equals

$$\text{Item } 51 - \frac{\text{Item } 51 \times \text{Item } 66}{100} - \frac{\text{Item } 51 \times \text{Item } 64}{100} - \frac{\frac{9}{8}\text{ Item } 51 \times \text{Item } 63}{100}$$

$$- \frac{\text{Item } 52 \times \text{Item } 68}{100}$$

Therefore,

$$\text{Item } 54 = \text{Item } 51 \left[1 - \frac{\text{Item } 66 + \text{Item } 64 + \frac{9}{8}\text{ Item } 63}{100} \right] - \frac{\text{Item } 52 \times \text{Item } 68}{100}$$

Item 55. $= \dfrac{\text{Item } 52 \times 100}{\text{Item } 51}$

Items 56 to 69. From chemist.
Items 69, *a*, *b*, *c*, *d*. The ultimate analysis of the ash will be made only in special cases to obtain data on the formation of clinker.

Item 70. $= \dfrac{\text{Item } 51}{\text{hours}}$

Item 71. $= \dfrac{\text{Item } 54}{\text{hours}}$

Item 72. $= \dfrac{\text{Item } 70}{\text{Item } 2}$

Item 73. $= \dfrac{\text{Item } 71}{\text{Item } 2}$

Item 74. $= \dfrac{\text{Item } 70}{\text{Item } 5}$

Item 75. $= \dfrac{\text{Item } 71}{\text{Item } 5}$

Item 76. "The rate of descent of dry coal through the fuel bed," or "The dry coal per cu. ft. of fuel bed per hour," which is the same, offers a means of comparing the rate of gasification in different producers that seems to be better adapted for the purpose than the expressions taken from boiler practice, viz: "coal per sq. ft. of grate area," or "coal per sq. ft. of fuel bed," the latter having been used in producer practice.

Item 76. $= \dfrac{\text{Item } 74}{\text{Item } 4}$

Item 77. $= \dfrac{\text{Item } 75}{\text{Item } 4}$

Item 78. Taken from chemist's report.

Item 79. $= \dfrac{\text{Item } 78 \times \text{Item } 51 - \text{Item } 52 \times \text{Item } 68 \times 145.40}{\text{Item } 54}$

Item 80. $= \left\{ \text{Item } 61 \times 145.40 + \text{Item } 65 \times 40.00 + [\text{Item } 62 - \tfrac{1}{8} \text{ of Item } 63] \times 620.00 \right\}$

Item 81. $= \dfrac{\text{Item } 80 \times \text{Item } 51 - \text{Item } 52 \times \text{Item } 68 \times 145.40}{\text{Item } 54}$

Item 113. Total volume of gas passing through meter at dryer. Observed.
Item 114. Total volume of standard gas passing through meter at dryer. Neglecting the effect of moisture.

Let p_1 = absolute pressure in inches Hg. at dryer meter.
t_1 = absolute temperature, deg. fahr. at dryer meter.
v_1 = total volume of gas passing through meter.
P, V, and T, be the condition of standard gas.
P = 30 in. Hg.
T = 460 + 62 = 522

Then

$$\frac{p_1 v_1}{t_1} = \frac{PV}{T}$$

$$\text{or } V = \frac{p_1 v_1 T}{P t_1} = \frac{p_1 v_1 \times 522}{30 t_1} = \frac{17.4 \ p_1 v_1}{t_1}$$

from which the value of Item 114 follows.

Item 114. $= 17.4 \dfrac{\text{Item 28} \times \text{Item 113}}{\text{Item 47}}$

Item 118. Not considered in these tests.

Item 119 and 119*a*. One cubic foot of standard gas, i. e. gas at a temperature of 62° Fahr. or 522° absolute and a pressure of 30 in. Hg. gives up the high value in the following table when the products of combustion are brought back to this temperature, and the moisture condensed. If the moisture is not condensed it gives the low value.

H_2 = 328 (high) or 276 (low) B. t. u per cu. ft. of standard gas.
C_2H_4 = 1610 (high) or 1510 (low) B.t.u. per cu. ft. of standard gas.
CO = 319 (both high and low) B. t. u. per cu. ft. of standard gas.
CH_4 = 1010 (high) or 910 (low) B.t.u. per cu. ft of standard gas.

Item 120. This quantity is the average of all the calorimeter determinations. Each separate determination by the calorimeter must be computed and the heating value obtained. The following formula may be used. The calorimeter readings are taken in centigrade units with the exception of the meter reading and pressure.

Let t_2 = temperature of entering water, deg. cent.
t_1 = temperature leaving water, deg. cent.
r = rise in temperature of water, deg. cent.
W = weight of water used during the intervals = 8 litres for all tests.
G_1 = cu. ft. of gas used from meter
t_g = temperature of entering gas, deg. cent.
p_g = pressure entering gas inches Hg. absolute, corrected for vapor pressure of water (see Item 25).
H = heating value per cu. ft. of standard gas (62 deg. Fahr. or 16.7 deg. Cent. and 30 in. Hg.)
t_s = temperature of standard gas = 62 deg. Fahr. or 16.7 deg. Cent.
p_s = pressure of standard gas = 30. in Hg.
G_s = cu. ft. of standard gas.

$$\frac{G_1 p_g}{T_g} = \frac{G_s p_s}{T_s}$$

$$G_s = \frac{G_1 \times p_g \times T_s}{T_g \times p_s}$$

Where T_g and T_s are in absolute deg. cent.,

$t_1 - t_2 = r$

Total heat per cu. ft. standard gas in B.t.u. = H
Total heat absorbed by water = W × r

$$H = \frac{W \times r \times 3.968}{G_s} = \frac{W \times r \times 3.968}{\dfrac{G_1 \times p_g \times T_s}{T_g \times p_s}}$$

$$= \frac{8 \times r \times 3.968 \times T_g \times 30}{G_1 \times p_g \times (16.7 + 273)} =$$

$$\frac{T_g \times r \times 3.29}{G_1 \times p_g}$$

where 3.968 is the conversion factor.

In this formula it is assumed that the exhaust products are brought back to 62° F. This is not strictly true but the error introduced is negligible, when the error in the use of the apparatus is considered. There is another error due to the exhaust products carrying out more or less vapor of water than was brought in by the entering gas and air.

This error will also be small and may either be positive or negative depending on conditions. The entering gas will in most cases come from direct contact with water and will therefore be saturated. The air ordinarily will not be saturated. On combustion, moisture will be formed by the union of the oxygen and hydrogen, there will be a contraction in volume of the gases due to the combustion, and also a contraction or expansion due to a change in temperature after combustion. In whichever direction the change in the weight of moisture in the out-going gas from that brought in by the entering gas may occur, this change may be considered very small; for the contraction on combustion will be comparatively small, and this contraction will partly offset the unsaturated condition of the air used for combustion. Also the change in temperature of the out-going gas from that of the entering gas will be small.

The heating values as given in Items 119 and 120 are the *high values*.

The values obtained from the analysis will be more accurate and will be used in all computations.

Item 121. The specific weights of the following gases at 62 deg. and 30 in. Hg. are

CO_2 = 0.11610	CH_4 = 0.04278
CO = 0 07362	C_2H_4 = 0.07370
O_2 = 0.08418	SO_2 = 0.16380
H_2 = 0.00530	H_2S = 0.08682

N_2 = 0.07400

Item 121. = [Item 135 × 0.1161 + Item 136 × 0.07362 + Item 137 × 0.08418 + Item 138 × 0.00530 + Item 139 × 0.04278 + Item 140 × 0.0737 + Item 141 × 0.1628 + Item 142 × 0.08682 + Item 143 × 0.0740] $\frac{1}{100}$

Item 144 to 152. Calculation of the gas analysis by weight from the analysis by volume. Assume that we have one cubic foot of gas at 62 deg. Fahr. and 20 in. Hg. of the following composition:

VOLUMETRIC ANALYSIS	SPECIFIC WEIGHT	ANALYSIS BY WEIGHT PER CENT
$CO_2 = a$ per cent	$0.1161 = W_a$	$A = \frac{W_a \times a}{W}$
$CO = b$	$0.07362 = W_b$	$B = \frac{W_b \times b}{W}$
$O_2 = c$	$0.08418 = W_c$	$C = \frac{W_c \times c}{W}$
$H_2 = d$	$0.00530 = W_d$	$D = \frac{W_d \times d}{W}$

$$CH_4 = e \qquad 0.04278 = W_e \qquad E = \frac{W_e \times e}{W}$$

$$C_2H_4 = f \qquad 0.07370 = W_f \qquad F = \frac{W_f \times f}{W}$$

$$SO_2 = g \qquad 0.16380 = W_g \qquad G = \frac{W_g \times g}{W}$$

$$H_2S = h \qquad 0.08682 = W_h \qquad H = \frac{W_h \times h}{W}$$

$$N_2 = i \qquad 0.07400 = W_i \qquad I = \frac{W_i \times i}{W}$$

Where $W = [a \times W_a + b \times W_b + c \times W_c + e \times W_e \ldots\ldots + i \times W_i]\frac{1}{100}$ = Item 121.

Item 122. The specific heats of the gases vary according to the pressure and temperature. As the pressure used throughout the experiments is atmospheric we have only to consider the variation with the temperature. The following formulae taken from Zeuner, vol. I, page 147, give the specific heat for constant volume C_v.

[1]$CO_2,\ mC_v = 6.50 + 0.00774t$ .... (1)
$H_2O,\ mC_v = 5.78 + 0.00572t$ .... (2)
$O_2\ H_2\ N_2,\ CO,\ mC_v = 4.76 + 0.00244t$ .... (3)
$mC_p - mC_v = 1.9934$ .... (4)

For the specific heat of marsh gas CH_4, our other constituent, we will use the value $C_p = 0.6$. This is approximate, but as the quantity of CH_4 is small the resultant error is consequently small.

In the above formula, m is the molecular weight of the gas, t the temperature in deg. cent. and C_v the mean specific heat between zero and t deg. cent. C_p is determined from formula (4). From the above formulas, the analysis by weight as determined below and the temperature of the gases leaving the producer, the specific heat of each constituent in a unit weight of the gas may be determined. The specific heat of the gas will be the sum of the specific heats of the constituents.

Substituting the value of mC_v from formula (4), and the value of m, and changing to deg. fahr. we have from the above formulas:

For $CO_2,\ C_p = 0.19 + .0000977t$ .... a
$H_2O,\ C_p = 0.426 + .000176t$ .... b
$H_2,\ C_p = 3.355 + .000678t$ c
$CO,\ C_p = 0.24 + .0000484t$ .... d
$N_2,\ C_p = 0.24 + .0000484t$ .... e
$CH_4,\ C_p = 0.6$ .... f
$O_2,\ C_p = 0.21 + .0000424t$ .... g

Let a, b, c, d, e and f, represent the mean C_p for the above gases between 32 deg. and t deg. Fahr. Then the C_p of the producer gas = the sum of the products of the constituents of the gas by weight × the specific heat of the constituent.

That is,

$$\text{Item }122 = [a \times \text{Item }144 + c \times \text{Item }147 + d \times \text{Item }145 + e \times \text{Item }152$$
$$+ f \times \text{Item }148 + g \times \text{Item }146]\ \frac{1}{100}$$

Item 123

1	2	3	4
$CO_2 = O_2 + C$	$CO = C + O$	$CH_4 = C + 2H_2$	$C_2H_4 = 2C + 2H_2$
$44 = 32 + 12$	$28 = 12 + 16$	$16 = 12 + 4$	$28 = 24 + 4$

Total weight of carbon appearing in a unit weight of gas from the above = per cent by weight $CO_2 \times \frac{3}{1100}$ + per cent by weight $CO \times \frac{3}{700}$ + per cent by weight $CH_4 \times \frac{3}{400}$ + per cent by weight $C_2H_4 \times \frac{6}{700}$

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[1] Mallard and Le Chatelier's Formulas.

The total weight of H_2 appearing in a unit weight of gas = per cent by weight $\frac{H_2}{100}$ + per cent by weight $CH_4 \times \frac{1}{400}$ + per cent by weight $C_2H_4 \times \frac{1}{700}$

or Item 123 = [Item 144 × 0.273 + Item 145 × 0.429 + Item 148 × 0.75 + Item 149 × 0.858] ÷ [Item 147 + Item 148 × 0.25 + Item 149 × 0.143]

Item 124. Observed.

Item 125. Let G = total volume of gas as measured by the meters.

p = absolute pressure of this gas in inches Hg. as observed.

T = absolute temperature in deg. fahr.

t = observed temperature.

The volume of gas G as measured by the meter is saturated with water vapor at the temperature t.

Let p_1 = pressure of this vapor in inches as obtained from the steam table.

Then as the pressure p is the total pressure of the mixture, the actual or partial presure of the dry gas is $P - p_1 = p_2$.

Let p_s, G_s, and T_s, be the condition of standard gas. Then

$$\frac{G_s \times p_s}{T_s} = \frac{G \times p_2}{T} \text{ or } G_s = \frac{G \times p_2 \times T_s}{T \times p_s} = \frac{G \times p_2 \times 522}{T \times 30} = \frac{G \times p_2}{T} \times 17.4$$

Therefore Item 125 equals

$$\frac{\text{Item 124} \times \text{Item 26} \times 17.4}{\text{Item 45}}$$

Item 126. Calculation of the volume of the gas from the analysis of the gas and the analysis of the coal. Evidently the total weight of the carbon appearing in the gas should be equal to the total weight of carbon in the coal minus the weight that is lost through the grate and the weight lost in soot and tar. This latter is small for the hard-coal producer and will be neglected.

Let P = Per cent carbon by weight in dry coal.

W = total weight of dry coal.

W_1 = total weight of ash and refuse.

P_1 = Per cent by weight of carbon in the ash and refuse.

W_2 = total weight of carbon that should appear in the gas, or the weight of carbon utilized in the producer.

$$W_2 = \frac{PW - P_1 W_1}{100}$$

This carbon is contained in the CO_2, CO, CH_4, C_2H_4.

The proportion by weight of C in CO_2 is 3/11, of C in CO is 3/7, of C in CH_4 is 3/4 and of C in C_2H_4 is 6/7.

Therefore the total weight of C contained in a unit weight of gas will be

$$W_3 = \frac{3/11\,A + 3/4\,E + 3/7\,F + 6/7\,G}{100}$$

Where A, E, F, and G are the per cent by weight of CO_2, CH_4, CO, and C_2H_4 from the gas analysis.

The per cent of this carbon contained in the gas as CO_2 is $\frac{3/11\ A}{W_3}$

The actual weight of this carbon will be $\frac{3/11\ A}{W_3 \times 100} W_2$. Since W_2 is the total weight of carbon utilized, from the fuel.

One pound of carbon on burning produces $3\frac{2}{3}$ lb. of CO_2.

$$W_2 \times \frac{3/11\ A}{W_3 \times 100} \times 3\tfrac{2}{3} = \text{total weight of } CO_2 \text{ in the gas.}$$

Let W_s = the specific weight of CO_2 at 62 deg. and 30 in. Hg. See Item 121. The standard volume V_s of CO_2 will therefore be,

$$\frac{A W_2}{100 \times W_3 \times W_s} = V_s$$

Let this volume equal a per cent (from the volumetric gas analysis) of the total volume of gas delivered by the producer. The total volume of standard gas from the gas analysis is therefore

$$\frac{100\ V_s}{a} = V^1_s$$

$$V^1_s = \frac{A \times W_2}{a \times W_3 \times W_s}$$

Item 126 therefore equals

$$\frac{\text{Item 144} \times (\text{Item 51} \times \text{Item 61} - \text{Item 52} \times \text{Item 68})}{0.116 \times \text{Item 135} \times (0.273\ \text{Item 144} + 0.75\ \text{Item 148} + 0.429\ \text{Item 145} + 0.858\ \text{Item 149})}$$

Item 127. Item 126 should be used as a check on Item 125. The difference between the two values should not exceed 5 per cent. Item 125 should be used in all computations.

$$\textit{Item}\ 128 = \frac{\text{Item 127}}{\text{hours}}$$

$$\textit{Item}\ 129 = \frac{\text{Item 127}}{\text{Item 51}}$$

$$\textit{Item}\ 130 = \frac{\text{Item 127}}{\text{Item 54}}$$

$$\textit{Item}\ 131 = \text{Item 127} \times \text{Item 121}$$

$$\textit{Item}\ 132 = \frac{\text{Item 131}}{\text{hours}}$$

$$\textit{Item}\ 133 = \frac{\text{Item 131}}{\text{Item 51}}$$

$$\textit{Item}\ 134 = \frac{\text{Item 131}}{\text{Item 54}}$$

Item 135 to 143 From chemist.

Items 104. The relative humidity, or per cent saturation is observed by means of a hair hygrometer. This may also be obtained from a wet and dry bulb thermometer, and a set of psychrometric tables.

Item 105. See Kent, page 484 for weights of air and moisture.

Let p = per cent saturation, or relative humidity, Item 104.

n = weight of moisture contained in one cu. ft. of saturated air at the observed temperature, Item 29.

$\frac{pn}{100}$ = weight of moisture in 1 cu. ft. of air as used.

If m = weight of 1 cu. ft. dry air at the observed temperature, then

$$\text{Item 105} = \frac{pn}{100m} \times 100 = \frac{pn}{m} = \text{Item 104} \times \frac{n}{m}$$

This formula is in error due to neglecting the vapor pressure of water; this is, however, negligible in the present case.

Item 82. Observed.

Item 83. Observed.

Item 84. = Item 82 — Item 83.

Item 86. The weight of water decomposed in the producer is evidently 9 times the weight of hydrogen formed, since 1 lb. of water on decomposition yields 1 lb. of hydrogen and 8 lb. oxygen. The total weight of hydrogen formed is equal to the total weight of free hydrogen appearing in the gas, plus the total weight of hydrogen appearing in the CH_4 in the gas, minus the total weight of hydrogen that is not in combination with oxygen in the coal.

Item 86, therefore, equals

$$9 \left[\frac{\text{Item 131 (Item 147} + 0.25\ \text{Item 148)} - \text{Item 51 (Item 62} - \tfrac{1}{8}\ \text{Item 63)}}{100}\right]$$

Item 87. Owing to the difficulty in obtaining the weight of moisture in the gases leaving the producer with a proper degree of accuracy by the use of a dryer, it will ordinarily be better to use Item 86 for this item.

Item 106. Obtained from gas analysis by weight, Items 144 to 152 inclusive.

Let A = per cent CO_2
B = per cent O_2
C = N_2 per cent

Let D = per cent H_2
E = per cent CH_4
F = per cent CO

$$\begin{array}{ccc} 1 & 2 & 3 \\ C + O_2 = CO_2 & C + O = CO & H_2 + O = H_2O \\ 12 + 32 = 44 & 12 + 16 = 28 & 2 + 16 = 18 \\ \frac{3}{11} + \frac{8}{11} = 1 & \frac{3}{7} + \frac{4}{7} = 1 & \frac{1}{9} + \frac{8}{9} = 1 \end{array}$$

From equation (1), one lb. of CO_2 requires $\frac{8}{11}$ lb. of O for its formation
From (2) one lb. CO requires $\frac{4}{7}$ lb, of O for its formation.
The total amount of O appearing in 1 lb. of the gas is therefore

$$\left(\frac{8}{11} A + \frac{4}{7} F + B\right) \times \frac{1}{100}$$

This O comes from that contained in the air, that contained in the coal, and from the water decomposed. The oxygen contained in the coal, however, is supposed to be united with hydrogen, and is therefore contained in moisture, which has been allowed for in the water decomposed.

Let W = total weight of gas.
Then the total weight of O used is

$$\frac{W}{100}\left(\frac{8}{11} A + \frac{4}{7} F + B\right)$$

Let W_2 = weight of water decomposed. From (3), 1 lb. of water decomposed liberates $\frac{8}{9}$ lb. of O.

Weight of O supplied by decomposition of water $= \frac{8}{9} W_2$

Let W_3 = total weight of O supplied by air.
From the above equation we have,

$$\left(\frac{8}{11} A + \frac{4}{7} F + B\right) \frac{W}{100} = \frac{8}{9} W_2 + W_3.$$

$$\text{or } W_3 = \frac{W}{100}\left(\frac{8}{11} A + \frac{4}{7} F + B\right) - \frac{8}{9} W_2 \ldots\ldots\ldots\ldots (4)$$

The weight of air used is therefore $\frac{W_3}{0.23}$, since the proportion by weight of O in air is 23, or

$$\frac{W_3}{0.23} = W_4 = \frac{1}{0.23}\left[\frac{W}{100}\left(\frac{8}{11} A + \frac{4}{7} F + B\right) - \frac{8}{9} W_2\right] \ldots\ldots\ldots\ldots (5)$$

$$\text{Therefore Item 106} = \left[\frac{\text{Item 131}}{100}\left(\frac{8}{11}\text{ Item 144} + \frac{4}{7}\text{ Item 145} + \text{Item 146}\right) - \frac{8}{9} \times \text{Item 87}\right]\frac{1}{0.23} \ldots\ldots\ldots\ldots (6)$$

The above computation may be made from the weight of nitrogen appearing in the gas. The nitrogen comes from the air used and from the nitrogen introduced with the fuel.

Let C per cent = weight of N_2 from analysis.
Let W as before = total weight of gas.

Then $\frac{CW}{100}$ = total weight of N_2 in the gas.

The weight of N_2 supplied by fuel will be $\frac{W_1H_1}{100}$, where W_1 equals the total weight of dry coal and H_1 is the per cent by weight of N_2 contained in the coal. We have therefore,

$$\frac{CW}{100} = \frac{W_1H_1}{100} + W_4$$

where W_4 = total weight of N_2 in the air.
The weight of air supplied is therefore

$$\frac{W_4}{0.77} = \left(\frac{CW}{100} - \frac{W_1H_1}{100}\right)\frac{1}{0.77} = W_5 = \left(\frac{CW - W_1H_1}{77}\right)$$

or Item 106 = (Item 131 × Item 152 − Item 51 × Item 64) $\frac{1}{77}$ ....(7)

The weight of air derived by formula (6) will be liable to error, due principally to the error in the determination of the total quantity of water decomposed, which may be large, and also to the neglecting of the SO_2 formed.

The weight determined by formula (7) will be in error due principally to the taking of the weight of N_2 from the analysis by difference.

The results obtained from formulae (6) and (7) should check within 5 per cent.

The results obtained by (7) are believed to be more accurate and will be used in all computations.

Item 107. This may be obtained direct from the calibration curve of the orifice. It should be compared with the two values obtained above.

Item 108. This will ordinarily be taken from Item 106.

Item 109 = $\frac{\text{Item 108}}{\text{Hours}}$

Item 110 = $\frac{\text{Item 108}}{\text{Item 51}}$

Item 111 = $\frac{\text{Item 108}}{\text{Item 54}}$

Item 112 = $\frac{\text{Item 108}}{\text{Item 131}}$

Item 85 = Item 84 + Item 85*b* + Item 85*c*.

Item 85*b* = $\frac{\text{Item 108} \times \text{Item 105}}{100}$

Item 85*c* = $\frac{\text{Item 49} \times \text{Item 50}}{100}$

Item 88 = Item 85 − Item 87

Item 89 = $\frac{\text{Item 87}}{\text{Item 85}}$

Item 90 = $\frac{\text{Item 87}}{\text{Item 131}}$

Item 91 = $\frac{\text{Item 87}}{\text{Item 51}}$

Item 92 = $\frac{\text{Item 87}}{\text{Item 54}}$

Item 93 = $\frac{\text{Item 87}}{\text{Item 108}}$

Item 94 = $\frac{\text{Item 85}}{\text{Item 51}}$

Item 95 = $\frac{\text{Item 85}}{\text{Item 54}}$

Item 96 = $\frac{\text{Item 85}}{\text{Item 108}}$

Item 97 = Observed

Item 98 = Observed

$$\textit{Item } 99 = \frac{\text{Item } 84}{\text{Hours}}$$

$$\textit{Item } 100 = \frac{\text{Item } 99}{\text{Item } 11}$$

$$\textit{Item } 101 = \frac{\text{Item } 87}{\text{Hours}}$$

$$\textit{Item } 102 = \frac{\text{Item } 85}{\text{Hours}}$$

$$\textit{Item } 103 = \frac{\text{Item } 97}{\text{Hours}}$$

$$\textit{Item } 115 = \text{Item } 114 \times \text{Item } 121$$

$$\textit{Item } 116 = \frac{\text{Item } 98 \times 0.2205}{\text{Item } 115}$$

$$\textit{Item } 117 = \frac{100 \text{ Item } 88}{\text{Item } 131}$$

Item 153 The grate efficiency is 100 times the ratio of the total B.t.u. in the fuel minus the B.t.u. in the fuel lost through the grate; to the total B.t.u. contained in the fuel. Therefore

$$\textit{Item } 153 = \frac{\text{Item } 51 \times \text{Item } 78 \times 100 - \text{Item } 52 \times \text{Item } 68 \times 14540}{\text{Item } 51 \times \text{Item } 78}$$

Item 154. The hot gas efficiency is 100 times the ratio of the total heat of combustion of the gas, plus the sensible heat of the dry gas, plus the total heat contained in moisture in the gas to the heat of combustion of the dry coal, plus the heat given by the entering air, by the coal as sensible heat, and by the moisture or steam supplied in air.

$$\textit{Item } 154 = 100 \left\{ \text{Item } 119 \times \text{Item } 127 + \text{Item } 122 \times \text{Item } 131\,(\text{Item } 39 - 62^\circ.) + \text{Item } 88\,[1116 + 0.6\,(\text{Item } 39 - 212)] \right\} \div \text{Item } 51 \times \text{Item } 78 + \text{Heat supplied in steam.}$$

The heat given the producer by air, and sensible heat in coal may be neglected if the room temperature is within 20° of the standard temperature 62°. With a producer of the contained vaporizer type or one which utilizes the sensible heat of the gas to make the steam the term "Heat supplied in steam" drops out of the equation.

Item 155. The cold gas efficiency is 100 times the ratio between the total heat of combustion of the gas, to the total heat of combustion of the coal plus heat supplied from outside sources. That is, $\text{Item } 155 = 100\dfrac{\text{Item } 119 \times \text{Item } 127}{\text{Item } 51 \times \text{Item } 78}$

The efficiency based on 100 % grate efficiency $= \dfrac{\text{Item } 155}{\text{Item } 158}$

$$\textit{Item } 157 = \frac{\text{Item } 156 \times \text{Item } 49}{0.02 \times \text{Item } 127}$$

$$\textit{Item } 158 = \frac{\text{Item } 97 \times 1000}{62.5 \times \text{Item } 127} = \frac{\text{Item } 97}{0.0625 \times \text{Item } 127}$$

HEAT BALANCE

DEBIT

Item a. Obtained from Item 78.

Items b, c, d, e, f. Using as a standard the temperature of 62° F., the heat given to the producer by the items *b* to *f* inclusive is in most cases negligible. The error at a temperature of 100° F. is less than 1 per cent for a producer of the contained vaporizer type. However, the formulas will be given for computation of these items.

$$\textit{Item } b = \text{Item } 110 \times 0.24\,(\text{Item } 30 - 62^\circ \text{ F.})$$

$\textit{Item } c = \dfrac{\text{Item } 85b \times (\text{H} - 1070)}{\text{Item } 51}$ where H = the total heat in 1 lb. saturated steam at the temperature of the fire room.

$$\textit{Item } d = \frac{\text{Item 49} \times \text{Item 50}}{100 \times \text{Item 51}} (\text{Item 30} - 62^\circ \text{ F.})$$

$$\textit{Item } e = 0.24 \times (\text{Item 30} - 62^\circ \text{ F.})$$

$$\textit{Item } f = \frac{\text{Item 82} (\text{Item 33} - 62^\circ \text{ F.})}{\text{Item 51}}$$

CREDIT.

$$\textit{Item } a = \text{Item 122} \times \text{Item 133} \times (\text{Item 39} - 62^\circ \text{ F.})$$

$$\textit{Item } b = \frac{\text{Item 117} \times \text{Item 133}}{100} [(\text{Item 39} - 212^\circ \text{ F.}) \times 0.6 + 1116]$$

$$\textit{Item } c = \text{Item 119} \times \text{Item 129}$$

$$\textit{Item } d = \frac{\text{Item 52} \times \text{Item 68}}{\text{Item 51}} \times 145.40$$

Item e This is very small and may be neglected.

$$\textit{Item } f = \frac{\text{Item 83}}{\text{Item 51}} (\text{Item 34} - 62^\circ \text{ F.})$$

Item g = Sum of Items on debit side — (Item *a* + Item *b* + Item *c* + Item *d* + Items *e* and *f*.)

PUBLICATIONS OF THE ENGINEERING EXPERIMENT STATION

**Bulletin No. 1.* Tests of Reinforced Concrete Beams, by Arthur N. Talbot. 1904.

**Circular No. 1.* High-Speed Tool Steels, by L. P. Breckenridge. 1905.

**Bulletin No. 2.* Tests of High-Speed Tool Steels on Cast Iron, by L. P. Breckenridge and Henry B. Dirks. 1905.

**Circular No. 2.* Drainage of Earth Roads, by Ira O. Baker. 1906.

**Circular No. 3.* Fuel Tests with Illinois Coal. (Compiled from tests made by the Technologic Branch of the U. S. G. S., at the St. Louis, Mo., Fuel Testing Plant, 1904-1907,) by L. P. Breckenridge and Paul Diserens. 1909.

**Bulletin No. 3.* The Engineering Experiment Station of the University of Illinois, by L. P. Breckenridge. 1906.

**Bulletin No. 4.* Tests of Reinforced Concrete Beams, Series of 1905, by Arthur N. Talbot. 1906.

**Bulletin No. 5.* Resistance of Tubes to Collapse, by Albert P. Carman. 1906.

**Bulletin No. 6.* Holding Power of Railroad Spikes, by Roy I. Webber. 1906.

**Bulletin No. 7.* Fuel Tests with Illinois Coals, by L. P. Breckenridge, S. W. Parr and Henry B. Dirks. 1906.

**Bulletin No. 8.* Tests of Concrete: I. Shear; II. Bond, by Arthur N. Talbot. 1906.

**Bulletin No. 9.* An Extension of the Dewey Decimal System of Classification Applied to the Engineering Industries, by L. P. Breckenridge and G. A. Goodenough. 1906.

**Bulletin No. 10.* Tests of Concrete and Reinforced Concrete Columns, Series of 1906, by Arthur N Talbot. 1907.

**Bulletin No. 11.* The Effect of Scale on the Transmission of Heat through Locomotive Boiler Tubes, by Edward C. Schmidt and John M. Snodgrass. 1907.

**Bulletin No. 12.* Tests of Reinforced Concrete T-beams, Series of 1906, by Arthur N. Talbot. 1907.

**Bulletin No. 13.* An Extension of the Dewey Decimal System of Classification Applied to Architecture and Building, by N. Clifford Ricker. 1907.

**Bulletin No. 14.* Tests of Reinforced Concrete Beams, Series of 1906, by Arthur N. Talbot. 1907.

**Bulletin No. 15.* How to Burn Illinois Coal without Smoke, by L. P. Breckenridge. 1908.

**Bulletin No. 16.* A Study of Roof Trusses, by N. Clifford Ricker. 1908.

**Bulletin No. 17.* The Weathering of Coal, by S. W. Parr, N. D. Hamilton, and W. F. Wheeler. 1908.

**Bulletin No. 18.* The Strength of Chain Links, by G. A. Goodenough and L. E. Moore. 1908.

**Bulletin No. 19.* Comparative Tests of Carbon, Metallized Carbon and Tantalum Filament Lamps, by T. H. Amrine. 1908.

**Bulletin No. 20.* Tests of Concrete and Reinforced Concrete Columns, Series of 1907, by Arthur N. Talbot. 1908.

**Bulletin No. 21.* Tests of a Liquid Air Plant, by C. S. Hudson and C. M. Garland. 1908.

**Bulletin No. 22.* Tests of Cast-Iron and Reinforced Concrete Culvert Pipe, by Arthur N. Talbot. 1908.

**Bulletin No. 23.* Voids, Settlement and Weight of Crushed Stone, by Ira O. Baker. 1908.

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